Impact of urban Growth on Air Quality:

A Case of Jaipur City

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by

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under the guidance of

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I, **Vikas Kumar**, hereby declare that this project titled **"Impact of urban Growth on Air Quality: A Case of Jaipur City"** is carried out by me in the **Department of Architecture and Planning** of Visvesvaraya National Institute of Technology, Nagpur. The work is original and has not been submitted earlier whole or in part for the award of any degree/diploma at this or any other Institution/University.

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This is to certify that the Project titled **"Impact of urban Growth on Air Quality: A Case of Jaipur City"** is submitted by **Vikas Kumar** in partial fulfilment of the requirements for the award of the degree of **Master of Technology in Urban Planning,** VNIT Nagpur. The work is comprehensive, complete and fit for final evaluation.

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-Vikas Kumar

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ABSTRACT

Urban growth in Indian cities is increasingly linked to rising environmental challenges, particularly air pollution. This study investigates the spatial impact of urban expansion on air quality in Jaipur City, Rajasthan. The primary objective is to analyze the relationship between population density, land use patterns, road infrastructure, and the Air Quality Index (AQI), with a focus on how urban sprawl contributes to air quality degradation.

Using a GIS-based spatial analysis framework, the study integrates population density maps, land use and land cover (LULC) data, and AQI records. Geographically Weighted Regression (GWR) is employed to identify spatial correlations and hotspot zones where population and road density have the strongest impact on air quality. The Sprawl Index further categorizes urban spread to highlight areas experiencing unplanned growth.

Findings reveal that Jaipur's peripheral zones—characterized by low population density and fragmented road networks—show higher AQI values due to greater dependence on private vehicles and poor dust control. Central areas with higher density and better infrastructure demonstrate relatively better air quality. The land use analysis of AQI hotspots shows dominance of residential and commercial activity in polluted areas, indicating inadequate infrastructure planning in fast-growing zones.

Based on these results, the study proposes three integrated recommendations: improving road infrastructure and dust control measures, establishing vegetative buffer zones, and promoting public transport accessibility. Each recommendation includes governance mechanisms, financing models, and implementation strategies that support sustainable urban management.

This research highlights the importance of spatial analysis in urban environmental planning and offers actionable policy insights. The approach used can serve as a model for other Indian cities facing similar urbanization and pollution challenges.

Keywords - Urban Growth, Jaipur City, Air Pollution, GIS, Geographically Weighted Regression (GWR), Sprawl Index, Hotspot Analysis, Spatial Correlation, Road Infrastructure, Dust Control Measures, Green Buffer Zones, Public Transport Accessibility

CONTENTS

1 BACKGROUND 1
1.1 INTRODUCTION 1
1.2 URBAN GROWTH 1
1.2.1 DEFINITIONS OF URBAN GROWTH 2
1.3 AIR QUALITY 3
1.4 CHALLENGES AND PROBLEMS IN JAIPUR CITY 4
1.4.1 SEVERAL AIR POLLUTION ISSUES IN JAIPUR 4
1.5 SYNOPSIS 5
2 LITERATURE STUDY 7
2.1 URBAN GROWTH 7
2.1.1 SIGNIFICANCE OF URBAN GROWTH. 7
2.1.2 TYPES OF URBAN GROWTH 8
2.2 AIR QUALITY 8
2.2.1 AIR POLLUTANTS 8
2.3 URBAN GROWTH AND AIR QUALITY 9
2.4 NORMS AND STANDARDS 10
2.4.1 INTERNATIONAL STANDARDS (WHO GUIDELINES) 10
2.4.2 NATIONAL STANDARDS (INDIA: NAAQS, CPCB) 10
2.4.3 AIR QUALITY INDEX (AQI) CATEGORIES (INDIA) 11
2.5 CASE STUDIES 11
2.5.1 COMMON THEMES AND FOCUS AREAS 12
2.5.2 METHODOLOGICAL APPROACHES 12
2.5.3 TOOLS AND TECHNIQUES 12
2.5.4 PURPOSE AND UTILITY 12
3 STUDY AREA 13

3.1 STUDY AREA SELECTION 13
3.2 LOCATION OF THE CITY 15
3.3 HISTORY, GROWTH AND DEVELOPMENT 15
3.4 TOPOGRAPHICAL FEATURES 17
3.5 CLIMATE 17
3.6 DEMOGRAPHY OF THE CITY 17
3.7 AIR POLLUTION IN JAIPUR 19
3.7.1 Air Quality Index (AQI) of Jaipur city 19
3.7.2 PM_{10} Concentrations: 19
3.7.3 SO_2 and NO_2: 19
3.7.4 Spatial Patterns: 20
3.7.5 Temporal Patterns: 20
4. DATA COLLECTION AND ANALYSIS 20
4.1 LULC MAP 20
4.1.1 BUILT-UP AREA CHANGES ANALYSIS 23
4.3.1 POPULATION GROWTH 26
4.3.2 POPULATION DENSITY DISTRIBUTION (2024) 26
4.3.3 ROAD NETWORK AND ROAD DENSITY 29
4.4.1 AIR QUALITY (ANNUAL COMPARISON) 33
4.4.2 AIR QUALITY (SEASONAL COMPARISON) 34
4.5 AIR QUALITY ANALYSIS 35
4.5.1 ANNUAL AQI TREND (OVERALL CHANGE) 35
4.6 LST MAP ANALYSIS 38
4.7 GIS LAYERS AND ANALYTICAL PURPOSE 40
4.8 INTERPRETATION OF MAPS 41
4.9 EXPANSION OF BUILT-UP AREA 41

4.9.1 GWR AND HOTSPOT MAPPING OF URBAN GROWTH–AIR QUALITY 44
4.9.2 MAJOR IMPACTED AREA 46
4.10 ANALYSIS OF FIELD SURVEY 48
5 RECOMMENDATIONS AND PROPOSALS: 53
5.1 POLICIES TO CONTROL AIR POLLUTION IN JAIPUR 53
5.1.1 This proposal is not covered under existing policies 54
5.2.1 WHAT THIS PROPOSAL ADDRESSES 54
5.3 STRENGTHENS OF PROPOSAL 55
5.3.1 HOTSPOT LOCATIONS 55
5.3.2 JUSTIFICATION FOR AQI HOTSPOT AREA 1 56
5.3.3 JUSTIFICATION FOR AQI HOTSPOT AREA 2 58
5.3.4 IMPLEMENTATION FRAMEWORK FOR AQI HOTSPOT AREAS 60
5.3.5 STRATEGIC DIMENSIONS 61
5.3.6 IMPLEMENTATION FRAMEWORK 61
5.3.7 FINANCING MECHANISMS 61
5.3.8 INCENTIVES & REVENUE OPTIONS 62
5.3.9 POLICY AND PLANNING IMPLICATIONS 62
5.4 PROPOSAL 2 63
5.4.1 JUSTIFICATION 63
5.4.2 KEY STRATEGIES 64
5.4.3 IMPLEMENTATION FRAMEWORK 64
5.5 PROPOSAL 3 65
5.5.1 JUSTIFICATION 65
5.5.2 KEY STRATEGIES 65
5.5.3 IMPLEMENTATION FRAMEWORK 66

5.6 CONCLUSION OF 66
5.7 KEY FINDINGS 66
5.8 RECOMMENDATIONS SUMMARY 67
5.9 LIMITATIONS OF THE STUDY 67
REFERENCES 68

LIST OF FIGURES

FIGURE 1 JAIPUR LOCATION MAP 15
FIGURE 2 URBANIZATION PATTERN 16
FIGURE 3 POPULATION 2024 MAP 18
FIGURE 4 POPULATION DENSITY MAP 2024 18
FIGURE 5 LULC JAIPUR (1991, 2001, 2011, 2021, 2024) 21
FIGURE 6 BUILT-UP AREA EXPANSION MAP 22
FIGURE 7 LAND-USE MAPS 25
FIGURE 8 POPULATION DENSITY MAP 2011 & 2024 27
FIGURE 9 ROAD NETWORK MAP 29
FIGURE 10 ROAD NETWORK MAP 30
FIGURE 11 ROAD CONDITION PICTURE 31
FIGURE 12 INDUSTRY, ROAD CONDITION & ROAD SIDE PARKING 32
FIGURE 13 ANNUAL AQI DIFFERENCE (2023 & 2000) 33
FIGURE 14 SEASONAL AQI COMPARISON (2023 & 2000) 34
FIGURE 15 LST MAP (2015 & 2025) 38
FIGURE 16 BUILT-UP AREA CHANGE (2001-2011) 41
FIGURE 17 BUILT-UP AREA CHANGE (2001-2024) 42
FIGURE 18 ROAD DENSITY R2 MAP 43
FIGURE 19 AQI HOTSPOT ANALYSIS MAP 43
FIGURE 20 SPRAWL R2 MAP 43
FIGURE 21 SPRAWL INDEX (HOTSPOT ANALYSIS) MAP 43
FIGURE 22 MAX HOTSPOT ANALYSIS MAP 44
FIGURE 23 MAX R2 MAP 44
FIGURE 24 LAND-USE MAP 2024 46
FIGURE 25 HOTSPOT LOCATION 1 55
FIGURE 26 HOTSPOT LOCATION 2 57

LIST OF TABLES

TABLE 1 WHO AQI STANDARDS.....10
TABLE 2 CPCB AQI STANDARDS.....10
TABLE 3AIR QUALITY INDEX (INDIA).....11
TABLE 4 COMPARATIVE TABLE OF CASE STUDIES.....11
TABLE 5 UEII RANGE.....24
TABLE 6 CASE STUDIES WHO USED UEII.....24
TABLE 7 EMISSION CONTRIBUTION BY SECTORS.....32
TABLE 8 INTERPRETATION OF SEASON AQI CHANGE.....37
TABLE 9 CASE STUDIES THAT USED GWR AND HOTSPOT ANALYSIS.....40
TABLE 10 INTERPRETATION OF MAPS.....41
TABLE 11 POLICY/REPORT FOR CONTROLLING AIR POLLUTION IN JAIPUR.....54
TABLE 12 PROPOSALS THAT NOT COVERED UNDER EXISTING POLICIES.....54
TABLE 13 STRENGTHENS OF PROPOSAL.....55
TABLE 14 CASE STUDIES THAT USED ROAD INFRASTRUCTURE IMPROVEMENT TO CONTROL AIR POLLUTION.....60
TABLE 15 IMPLEMENTATION FRAMEWORK.....60
TABLE 16 STRATEGIC DIMENSION.....61
TABLE 17 IMPLEMENTATION FRAMEWORK.....61
TABLE 18 FINANCING MECHANISMS.....61
TABLE 19 INCENTIVES & REVENUE OPTIONS.....62
TABLE 20 IMPLEMENTATION FRAMEWORK FOR PROPOSAL 2.....64
TABLE 21 IMPLEMENTATION FRAMEWORK FOR PROPOSAL 3.....66

1 BACKGROUND

1.1 INTRODUCTION

Over the last three decades, Jaipur has experienced rapid and sustained urbanization, with its population rising from approximately 1.5 million in 1991 to over 4 million by 2021, and the built-up area expanding from around 112 km² to more than 467 km² (Census of India; Jaipur Master Plan 2025). This substantial urban growth has been closely linked to a marked deterioration in air quality across the city. According to the IIT Kanpur Source Apportionment Study (RPCB), annual average PM10 concentrations have consistently surpassed the national ambient air quality standard (NAAQS) of 100 µg/m³ (arthapedia, n.d.), reaching as high as 216 µg/m³ in 2020, while PM2.5 levels have climbed to 98 µg/m³, significantly exceeding the standard of 60 µg/m³. The primary sources contributing to Jaipur's air pollution include road dust (accounting for 35% of PM2.5 and 68% of PM10), vehicular emissions, and ongoing construction activities. Pollution levels also show strong seasonal variation, with the winter months experiencing the highest concentrations due to temperature inversions and increased burning of biomass. Despite the implementation of policy measures such as the National Clean air Programme and the Jaipur Master Plan 2025, challenges related to enforcement and persistent data gaps, especially in peri-urban and rapidly developing areas, remain. These problems show that people are counting on us to do better—and quickly, integrated Urban Planning and Environmental management strategies to address Jaipur's worsening air quality.

1.2 URBAN GROWTH

Urban growth refers to the way cities expand and become physically larger over time, population, and the intensity of land use, fundamentally reshaping urban landscapes and influencing economic, social, and environmental dynamics. It can be defined as "any type of growth of the urban environment," encompassing expansion in land area, population, or infrastructure (Singh, 2022) .More specifically, it is described as "the rate at which the population of an urban area increases" (Ghose), Urban expansion occurs when a city's boundaries extend into the surrounding rural landscape (Mundia, 2010). In contrast, the term urbanization describes the growing percentage of individuals living in cities compared to those in the countryside (Nations., n.d.). Urban growth is typically driven by factors such as migration, economic development, and increased demand for housing and infrastructure, and while it can stimulate economic opportunities, it also presents challenges including congestion,

pollution, and environmental degradation (Nations., n.d.). Understanding these definitions and the dynamics of urban growth is essential for effective urban planning and the pursuit of sustainable city development.

Urban open areas are vital to city life, offering sites for recreation, community interaction, and ecological sustainability. The definition of open space has changed over time, influenced by various cultural and academic viewpoints from different nations (World Health Organization, 2016)). For example, in Western contexts, open spaces are often designed for leisure and environmental benefits, whereas in densely populated Asian cities, they may prioritize multifunctional uses (Jim, 2003).

1.2.1 DEFINITIONS OF URBAN GROWTH

- **Michael Pacione (2005)**

"Urban growth refers to the increase in the spatial extent and population of urban areas, driven by natural increase and migration, and often resulting in significant changes to land use, infrastructure, and environment." Source: "Urban Geography: A Global Perspective" (Pacione, 2009)

- **Peter Hall (1996)**

"Urban growth is the process by which cities expand in size and influence, incorporating surrounding lands and transforming them through social, economic, and spatial development." Source: "Cities of Tomorrow" (Hall, (2014))

- **United Nations (UN-Habitat, 2008)**

"The expansion of urban areas—marked by more and larger cities and a growing urban population—usually brings about increased pressure on services, infrastructure, and city management." ((UN-Habitat), 2008)

- **Harvey S. Perloff (1960s)**

"Urban growth, characterized by a city's demographic and spatial enlargement, must be managed through integrated planning to ensure optimal land use and sustainable outcomes." (Perloff, 1960)

- **Edward Glaeser (2011)**

"Cities tend to grow because they provide opportunities for prosperity, learning, environmental benefits, better health, and improved well-being, which draws more people and fuels their outward expansion." (Glaeser, 2011)

- **World Bank (1999)**

> "Urban growth encompasses both the quantitative expansion of urban areas and the qualitative transformation of their economies, demographics, and land use." (Bank & Yusuf, Entering the 21st Century: World Development Report, 1999/2000, 1999)

Urban growth describes the expansion in a city's size, population, and density of cities- a process that has dramatically accelerated in recent centuries. Only around 3% of people worldwide lived in cities in 1800; by 1950, that proportion had grown to 30% (United Nations, World Urbanization Prospects: The 2018 Revision, 2018), and by 2020, more than 56% of people globally resided in cities. Urban populations have grown from roughly 220 million in 1900 to over 4.4 billion in 2020. This rapid growth was initially driven by the Industrial Revolution in Europe and North America, and more recently by industrialization and migration in Asia, Africa, and Latin America. For example, between 1950 and 2020, the urban population in Asia increased from about 232 million to over 2.3 billion, representing nearly a tenfold rise. Today, urban growth continues to reshape societies, economies, and environments, making it a central issue for sustainable development and city planning ((Max Roser, 2024); (Bank, Urban development, 2025); (United Nations, World Urbanization Prospects: The 2018 Revision, 2018)).

1.3 AIR QUALITY

Air quality measures the extent to which the air in an environment is free from pollutants, determined by the presence and concentration including harmful agents like particulate matter (PM), nitrogen oxides (NO_x), sulfur dioxide (SO_2), carbon monoxide (CO), ozone (O_3), and other pollutants. Good air quality means the air is largely free from these pollutants, while poor air quality is characterized by elevated levels that can harm human health, ecosystems, and infrastructure. Air quality is often measured using indicators such as the Air Quality Index (AQI), which represents the levels of major pollutants present in the air at a particular site ((EPA), 2023). The World Health Organization highlights that air pollution-caused by sources such as vehicles, industry, household combustion, and agriculture-is a major environmental health risk, contributing to respiratory and cardiovascular diseases and millions of premature deaths annually (Organization, Ambient (outdoor) air quality and health, 2023). Monitoring and improving air quality is therefore essential for protecting public health, supporting environmental sustainability, and mitigating climate change impacts (Organization, Ambient (outdoor) air quality and health, 2023)

1.4 CHALLENGES AND PROBLEMS IN JAIPUR CITY

Jaipur faces severe air quality challenges, with annual average PM10 levels reaching 139 µg/m³ and PM2.5 levels averaging 87.5 µg/m³ in 2025-both well above World Health Organization and Indian national standards. The city's AQI has worsened from 116 in 2020 to 133 in 2025, frequently entering the "poor" category, especially in industrial and high-traffic areas like Police Commissionerate and Adarsh Nagar, where AQI values have peaked above 300 during winter and pre-monsoon months. Major pollution sources include road dust, vehicular emissions, construction activities, and seasonal dust storms. Health impacts are significant, with air pollution in Jaipur in 2025 equated to smoking nearly two cigarettes per day, contributing to rising rates of respiratory and cardiovascular diseases.

1.4.1 SEVERAL AIR POLLUTION ISSUES IN JAIPUR

Jaipur's air pollution is dominated by high levels of particulate matter, with PM10 concentrations often 2–4 times higher than national standards in both summer and winter, and PM2.5 levels similarly elevated-especially in winter, when they can reach 2.4–6.5 times the standard. The principal contributors to PM pollution are road dust (up to 46%), vehicular emissions (8%), construction activities, and industrial sources (7%), as detailed in recent emission inventory and source apportionment studies. Gaseous pollutants, including nitrogen oxides (NOx) and carbon monoxide (CO), also frequently exceed safe limits, with vehicles accounting for the majority of CO emissions and industries being the main source of SO_2. The chemical composition of PM in Jaipur reflects these sources, with higher concentrations of combustion-related pollutants in winter. Other factors such as inadequate municipal waste management, seasonal dust storms, and the use of solid fuels for cooking in low-income households further amplify particulate and toxic gas levels, particularly during winter temperature inversions. Studies identify citywide uniformity in high pollution levels, with industrial and high-traffic areas among the most polluted, and recommend comprehensive, multi-sectoral interventions for effective air quality management *(Sharma & al., 2020)*.

1.5 SYNOPSIS

AIM

To assess and analyze the impact of urban growth on air quality in Jaipur city.

OBJECTIVES

- To analyze the urban growth patterns in Jaipur.
- To measure and evaluate the levels and trends of key air pollutants.
- To determine the relationship between urban growth variables and air pollution levels.
- To identify the main sources contributing to air pollution in the context of urban growth.
- To evaluate the effectiveness of current air quality management and urban planning strategies.
- To propose recommendations for urban planning interventions and policy strategies to improve air quality in Jaipur.

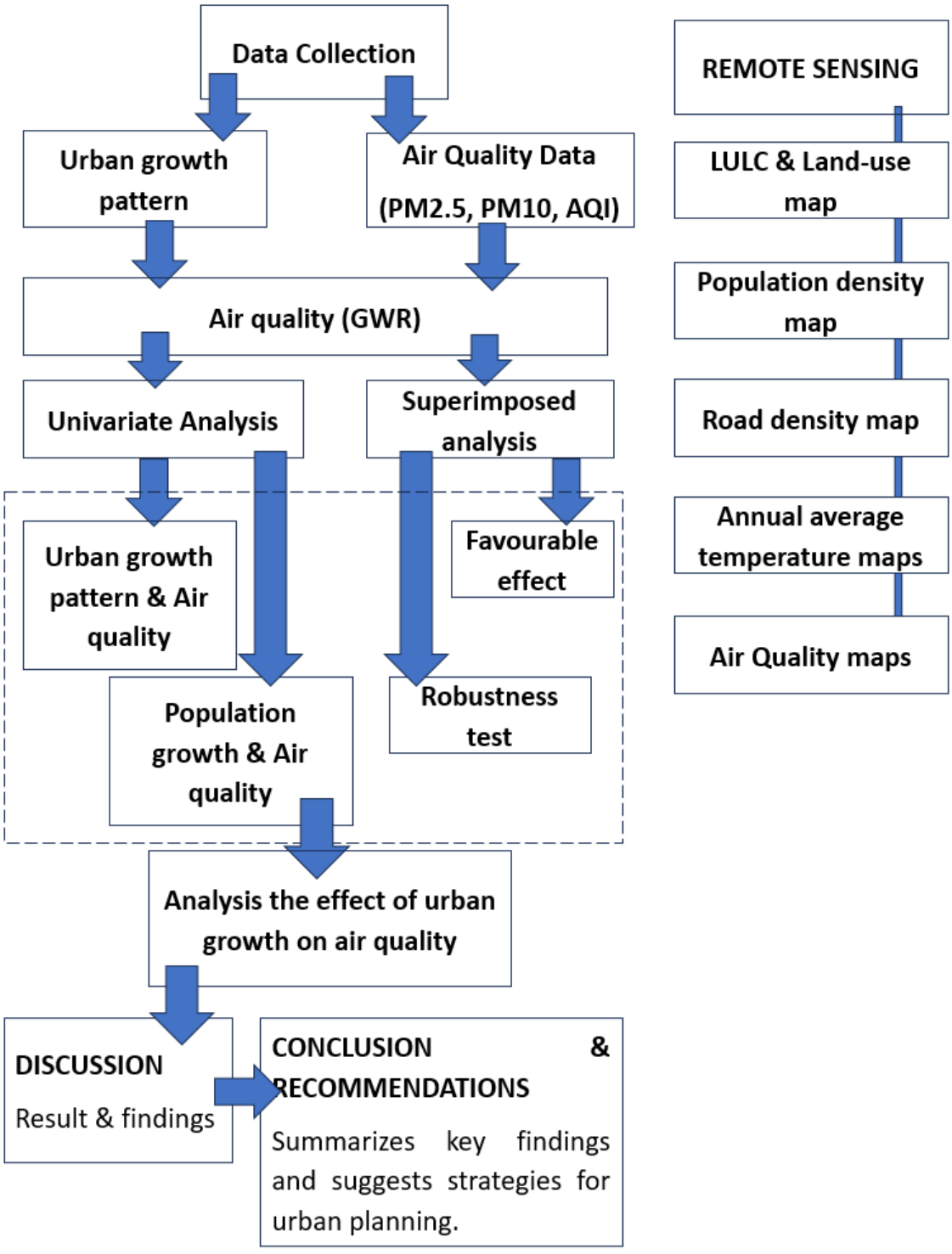
SCOPES

- This study focuses on Jaipur city, analysing air quality (PM10, PM2.5) and urban growth (land use, population density, built-up area, Road density) over the last 10–20 years.
- It integrates ground monitoring, satellite imagery, GIS, and government data to correlate urban expansion with pollution trends.
- The aim is to inform sustainable planning and localized mitigation strategies.

LIMITATIONS

- The study relies on secondary data sources (e.g., satellite images, government AQI reports), which may have spatial or temporal inconsistencies.
- Meteorological influences such as wind patterns, humidity, and regional pollution sources (e.g., from neighbouring districts) are not fully isolated in the analysis.
- Limited availability of real-time ground-level AQI monitoring stations, especially in the urban periphery, may affect the precision of localized pollution assessments.
- The study focuses primarily on particulate matter pollution ($PM_{2.5}$ and PM_{10}) and does not deeply explore gaseous pollutants (NOx, CO, SO_2) due to data constraints.

METHODOLOGY



2 LITERATURE STUDY

2.1 URBAN GROWTH

2.1.1 SIGNIFICANCE OF URBAN GROWTH.

- **Economic Growth and Job Creation:** Urban growth stimulates local and national economies by attracting businesses, fostering innovation, and creating diverse job opportunities. Well-planned urban expansion increases productivity, property values, and investment, driving overall economic development (Bank & Yusuf, Entering the 21st Century: World Development Report, 1999/2000, 1999).

- **Improved Infrastructure and Services:** Expanding cities enable better access to healthcare, education, transportation, and public utilities, leading to higher literacy rates, longer life expectancy, and improved emergency care (World.bank.).

- **Social Inclusion and Cultural Opportunities:** Urban growth enhances access to social services, cultural activities, and political participation, fostering a more inclusive and vibrant society (UN-Habitat.).

- **Environmental Challenges and Opportunities:** While urban growth can lead to deforestation, loss of green spaces, and pollution, it also presents opportunities for sustainable land use, efficient resource management, and the implementation of green infrastructure to mitigate environmental impacts (Surma).

- **Technological and Educational Advancement:** The concentration of educational institutions and research centers in growing urban areas promotes knowledge exchange, technological innovation, and skill development, further supporting economic and social progress (Zhang, 2025).

- **Enhanced Quality of Life:** Urban living offers easier access to information, healthcare, and social networks, contributing to better health outcomes, family planning awareness, and overall quality of life (Vlahov).

2.1.2 TYPES OF URBAN GROWTH

- **Infilling (Infill Growth):** Development that fills in vacant or underused land within existing urban areas, increasing density and making use of already serviced land. (Bhatta, 2010)
- **Edge Expansion (Edge or Lateral Growth):** Urban development that extends outward from the existing urban edge, gradually expanding the city's boundaries into adjacent rural or undeveloped land (Bhatta, 2010).
- **Outlying (Leapfrog or Peripheral Growth):** New urban development that occurs separated from the main urban area, often creating isolated patches or satellite settlements beyond the current urban fringe (Alberti, 2005).
- **Vertical Growth (Upward Growth):** Increase in the density and height of buildings within the existing urban footprint, often seen in rapidly developing cities with limited horizontal space (Bhatta, 2010).
- **Horizontal Growth (Outward Growth):** Expansion of the city's land area through the spread of low-density development, typically associated with urban sprawl (Bhatta, 2010).

2.2 AIR QUALITY

Air quality refers to the degree to which the air in a specific location is free from pollutants, with "good" air quality indicating low concentrations of harmful substances and "poor" air quality signifying elevated pollutant levels that can adversely affect human health, ecosystems, and property. Air pollutants are substances present in the atmosphere at concentrations above their normal background levels, including gases, particulates, and biological molecules (Organization, Ambient (outdoor) air quality and health, 2023).

2.2.1 AIR POLLUTANTS

- **PARTICULATE MATTER (PM10, PM2.5)**

Fine particles from vehicle exhaust, construction, road dust, and industrial emissions are primary indicators of urban air pollution. PM2.5 and PM10 are especially harmful as they These tiny particles can reach deep into your lungs and bloodstream, raising the risk of breathing and heart problems (Sharma & al., 2020).

- **GASEOUS POLLUTANTS**

  - **Nitrogen Oxides (NOx):** Emitted mainly from vehicles and industrial combustion, NOx contributes to respiratory problems and the formation of ground-level ozone (Sharma & al., 2020).

  - **Sulphur Oxides (SOx):** Produced by burning fossil fuels, especially coal, SOx can cause acid rain and respiratory issues (Sharma & al., 2020).

  - **Carbon Monoxide (CO):** A product of incomplete combustion, mainly from vehicles, CO reduces oxygen delivery in the body (Sharma & al., 2020).

  - **Ozone (O_3):** Formed by chemical reactions between NOx and VOCs in sunlight, ground-level ozone is a key component of smog and can trigger asthma and other health problems (Sharma & al., 2020).

  - **(VOCs) and Hazardous Air Pollutants:** Emitted from vehicles, industry, and waste burning, these include benzene, toluene, and heavy metals, which have carcinogenic and toxic effects (Surma).

2.3 URBAN GROWTH AND AIR QUALITY

- **Increased Emissions:** More vehicles, industries, and construction activities raise pollutant levels.
- **Land-Use Changes:** Reduction in green spaces and increased impervious surfaces worsen air pollution and urban heat islands.
- **Spatial and Temporal Variation:** Pollution hotspots often align with industrial, high-traffic, and densely populated areas.
- **Health Impacts:** Studies link urban air pollution to higher rates of asthma, COPD, heart disease, stroke, and even lung cancer, especially among vulnerable populations.

2.4 NORMS AND STANDARDS

2.4.1 INTERNATIONAL STANDARDS (WHO GUIDELINES)

As per the guidelines for global air quality given by The World Health Organization (WHO) that are often more stringent and serve as a reference for health-based standards ((WHO), WHO global air quality guidelines: Particulate matter ($PM_{2.5}$ and PM_{10}), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide., 2021)

Pollutant	Annual Mean (µg/m³)	24-hour Mean (µg/m³)
PM2.5	5	15
PM10	15	45
NO_2	10	25
SO_2	-	40
O_3	-	100 (8-hr mean)
CO (mg/m³)	-	4 (24-hr mean)

Table 1 WHO AQI standards

2.4.2 NATIONAL STANDARDS (INDIA: NAAQS, CPCB)

The Central Pollution Control Board (CPCB) of India sets the **National Ambient Air Quality Standards (NAAQS)**, which are applicable nationwide for key pollutants. The latest revision was in 2009 and covers 12 pollutants, including PM10, PM2.5, NO_2, SO_2, CO, O_3, NH_3, Pb, Benzene, Benzo(a)pyrene, Arsenic, and Nickel. These standards are designed to protect human health and the environment and are enforced under the Air (Prevention and Control of Pollution) Act, 1981 ((CPCB), 2025).

Pollutant	Annual Average (µg/m³)	24-hour Average (µg/m³)
PM10	60	100
PM2.5	40	60
NO_2	40	80
SO_2	50	80
O_3 (Ozone)	100 (8-hr)	180 (1-hr)
CO (mg/m³)	2 (8-hr)	4 (1-hr)
NH_3	100	400
Pb (Lead)	0.5	1.0

Table 2 CPCB AQI standards

2.4.3 AIR QUALITY INDEX (AQI) CATEGORIES (INDIA)

The AQI in India is calculated based on eight pollutants and categorized as follows

AQI Category	AQI Range	PM10 (µg/m³)	PM2.5 (µg/m³)	NO_2 (µg/m³)	SO_2 (µg/m³)	CO (mg/m³)
Good	0–50	0–50	0–30	0–40	0–40	0–1.0
Satisfactory	51–100	51–100	31–60	41–80	41–80	1.1–2.0
Moderately Polluted	101–200	101–250	61–90	81–180	81–380	2.1–10
Poor	201–300	251–350	91–120	181–280	381–800	10–17
Very Poor	301–400	351–430	121–250	281–400	801–1600	17–34
Severe	401–500	430+	250+	400+	1600+	34+

Table 3Air Quality Index (India)

2.5 CASE STUDIES

Title / Focus	Objectives	Aim	Methodologies	Tools
Urban Growth and Environmental Challenges: A Case Study of Jaipur City	Examine the relationship between urban growth and environmental challenges in Jaipur	To analyze how urbanization impacts air quality and environment	Review of urban growth trends, pollution data analysis	Statistical analysis, secondary data
Air Pollution Trends in Jaipur, UNESCO World Heritage City	Assess spatial and temporal trends of air pollution in Jaipur	To map pollution hotspots and understand pollution dynamics over time	Secondary data analysis (RSPCB), satellite imagery, GIS-based spatial analysis, interpolation (Kriging, IDW)	GIS (ArcGIS 10.4), NRSC BHUVAN satellite data
Urbanization and Air Environment in Jaipur	Study the impact of urbanization on Jaipur's air environment	To understand how urban growth patterns affect air quality	Literature review, analysis of urbanization and pollution data	Statistical data, urbanization indicators
Environmental Effects of Urban Traffic: A Case Study of Jaipur City	Assess environmental impact of urban traffic	To evaluate how traffic patterns contribute to air pollution	Traffic data analysis, pollution measurement	Geospatial analysis, pollution sensors
Air Quality Analysis for Jaipur, India (Monitoring, Satellite, and Emissions)	Monitor air quality using multiple data sources	To provide a comprehensive air quality assessment	Data collection from monitoring stations, satellite data, emission inventory	Satellite imagery, emission inventory tools
Impact of Urbanization and Industrial Growth on Pollution Levels in Jaipur	Evaluate how urbanization and industrial growth affect pollution	To link urban/industrial expansion with air quality changes	Analysis of pollution data, industrial/urban growth trends	Secondary data, statistical correlation
Jaipur Nagar Nigam (Greater) (Municipal Report, Urban Land Use & Environment)	Document land use and environmental status	To inform municipal planning and environmental management	Compilation of land use data, environmental monitoring	GIS, municipal surveys
Changing Urban Land Use and Its Impact on the Environment (Jaipur)	Assess impact of land use change on environment	To analyze consequences of urban expansion	Land use mapping, environmental impact assessment	GIS, remote sensing
Spatial and Temporal Variations in Air Quality Across Jaipur	Map and analyze air quality variations across Jaipur	To identify pollution hotspots and temporal trends	Pollution data analysis, GIS-based mapping, interpolation	GIS, pollution monitoring data

Table 4 Comparative table of Case studies

A comparative overview of various studies or projects focused on air quality, urbanization, and environmental challenges in Jaipur City. Here's an inference based on the data:

2.5.1 COMMON THEMES AND FOCUS AREAS

- **Urban Growth and Pollution:** A significant number of studies examine how urbanization and land use changes impact air quality and environmental conditions.
- **Air Quality Monitoring:** Several entries focus on monitoring air pollution trends and identifying hotspots using various methods.
- **Traffic and Transportation Impact:** Studies specifically address the role of vehicular emissions and urban traffic patterns in contributing to air pollution

2.5.2 METHODOLOGICAL APPROACHES

- **Data Analysis and GIS Tools:** The majority of the studies use spatial analysis through GIS and remote sensing, emphasizing the importance of geospatial data in environmental research.
- **Field Sampling and Pollution Measurement:** Some projects employ direct sampling methods and pollution sensors to gather empirical data on pollutant levels.
- **Secondary and Statistical Data Analysis:** Secondary data and statistical tools are widely used to analyze trends.

2.5.3 TOOLS AND TECHNIQUES

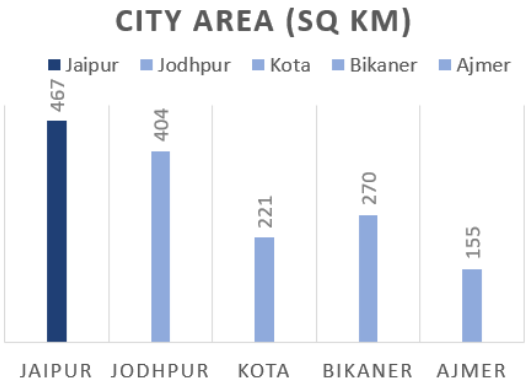
- **GIS and Remote Sensing:** These are the most frequently used tools across projects for spatial mapping and trend analysis.
- **Pollution Sensors and Emission Inventories:** Used for real-time and comprehensive air quality assessments.
- **Statistical Analysis Software (e.g., ArcGIS):** Common for handling environmental and urban data.

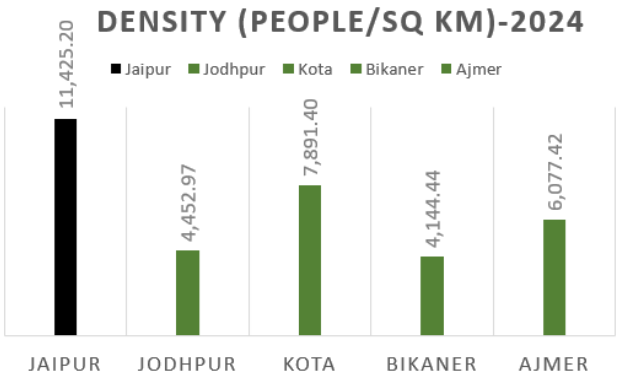
2.5.4 PURPOSE AND UTILITY

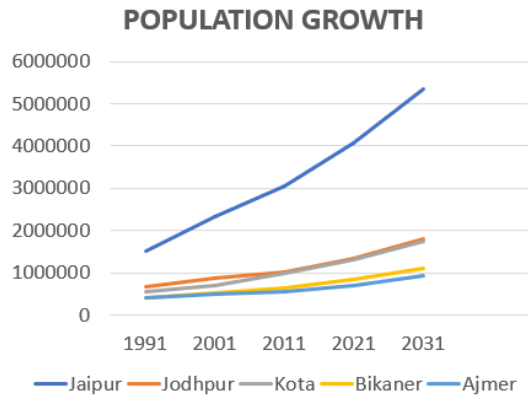
- These studies aim to support
    - Urban planning and sustainable development strategies.
    - Policy decisions related to pollution control.
    - Public awareness regarding environmental impacts of urban expansion.

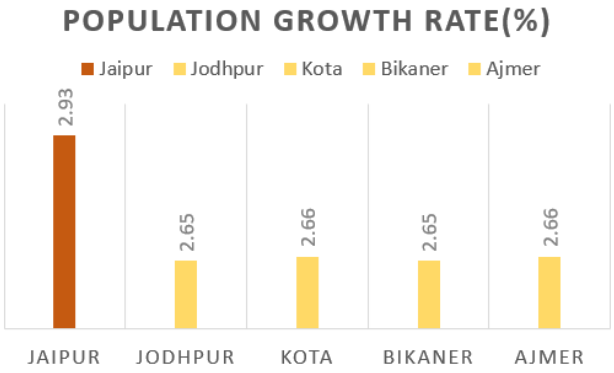
3 STUDY AREA

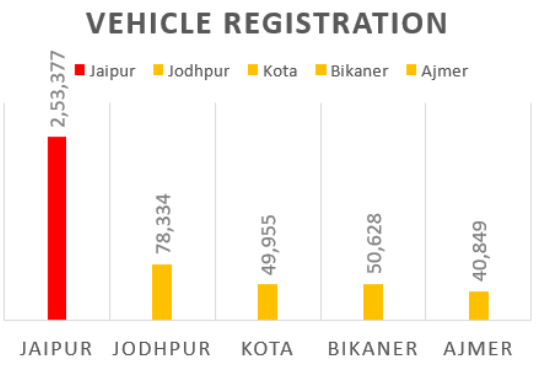
3.1 STUDY AREA SELECTION

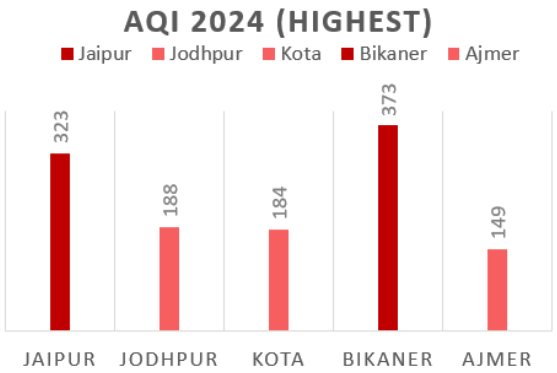












Among the major cities of Rajasthan, Jaipur distinctly emerges as the most critically impacted urban center in terms of population growth, urban density, vehicular pressure, and air quality degradation, making it a highly suitable focus for this study. Jaipur has the largest city area (467 sq. km) and, more significantly, the highest population density in 2024, recorded at 11,425.20 people per sq. km. The city's population has seen consistent exponential growth from 1991 to 2021, and projections for 2031 indicate continued expansion. Jaipur's annual population growth rate of 2.93% is the highest among the compared cities, clearly indicating the pace of urbanization.

This rapid growth has led to an unprecedented rise in private vehicles, with 2,533,377 vehicle registrations—over 30 times more than Jodhpur or Kota—highlighting the increasing dependency on personal transport. This surge in vehicular movement, coupled with expanding built-up areas and declining green cover, has significantly worsened the city's air quality. In 2024, Jaipur recorded an AQI peak of 323, placing it in the "very poor" category as per national air quality standards. This reflects the cumulative impact of urban sprawl, traffic congestion, poor dust control, and limited ecological buffers.

Compared to other cities like Ajmer or Kota, which have smaller urban footprints and lower vehicle numbers, Jaipur demonstrates a much higher environmental burden. These indicators strongly justify selecting Jaipur as the primary case study for analysing the impact of urban growth on air quality. The city presents a complex yet representative model of the challenges that fast-growing Indian cities faces in balancing development and environmental sustainability.

- Highest population density in 2024: 11,425.20 people/sq.km
- Fastest population growth rate: 2.93%
- Largest vehicle registrations: 2.53 million, highest in Rajasthan
- Highest AQI in 2024: 323 (Very Poor)
- Rapid urban sprawl and expansion into peripheral areas
- High dependency on private vehicles due to lack of public transport
- Major contributor to PM_{10} and $PM_{2.5}$ pollution

3.2 LOCATION OF THE CITY

Jaipur is the capital of Rajasthan, located in northwestern India at approximately 26°55′N latitude and 75°49′E longitude (Britannica, 2025), with an elevation of about 431m above sea level. The city sits on the eastern edge of the Thar Desert and is surrounded by the Aravalli hills on three sides, which provide natural protection from desert winds. Jaipur lies about 268 km southwest of New Delhi and is well connected by road, rail, and air to major Indian cities. The city's location at the intersection of historic trade routes and its proximity to natural features like the Aravalli range and Sambhar Lake have contributed to its growth as a major cultural, economic, and tourist hub in Rajasthan (Corporation), 2025).

Figure 1 Jaipur Location map

(Bala, 2020)

3.3 HISTORY, GROWTH AND DEVELOPMENT

Jaipur, the capital of Rajasthan, was founded in 1727 by Maharaja Sawai Jai Singh II (Centre, 2025), who envisioned a new, well-planned city due to the growing population and water scarcity in Amber, the former capital. Designed with the help of architect Vidyadhar Bhattacharya and guided by the principles of Vastu Shastra and Shilpa Shastra, Jaipur became India's first planned city, featuring a distinctive grid pattern, wide avenues, fortified walls, and seven gates. The city quickly flourished as a centre of trade, culture, and administration, with its iconic pink-painted buildings earning it the nickname "Pink City" after a royal visit in 1876. In the 19th and 20th centuries, Jaipur expanded beyond its original walls, adding civic buildings, schools, hospitals, and modern infrastructure. Its strategic relations with the British preserved its autonomy and promoted further development. After independence, Jaipur became

the capital of Rajasthan in 1956 and has since experienced rapid urban growth, with the population rising from about 160,000 in 1900 to over 4.4 million today. The city's expansion now extends far beyond the historic core, presenting new challenges in infrastructure, environment, and sustainable development, yet Jaipur retains its unique architectural heritage and planned urban character. (Corporation), 2025)

Jaipur becomes part of the Indian Union.
1947
The First Five-Year Plan is initiated, focusing on economic reconstruction and development.
1952
Establishment of RIICO to promote industrial development.
1979
Focus on establishing Defence Manufacturing Hubs and specialized industrial parks.
2010 onwards
1949
Jaipur is declared the capital of the newly formed state of Rajasthan.
1960s
The Green Revolution increase agricultural productivity
1991
Major economic liberalization reforms are introduced, transforming industrial policies and attracting foreign investment.

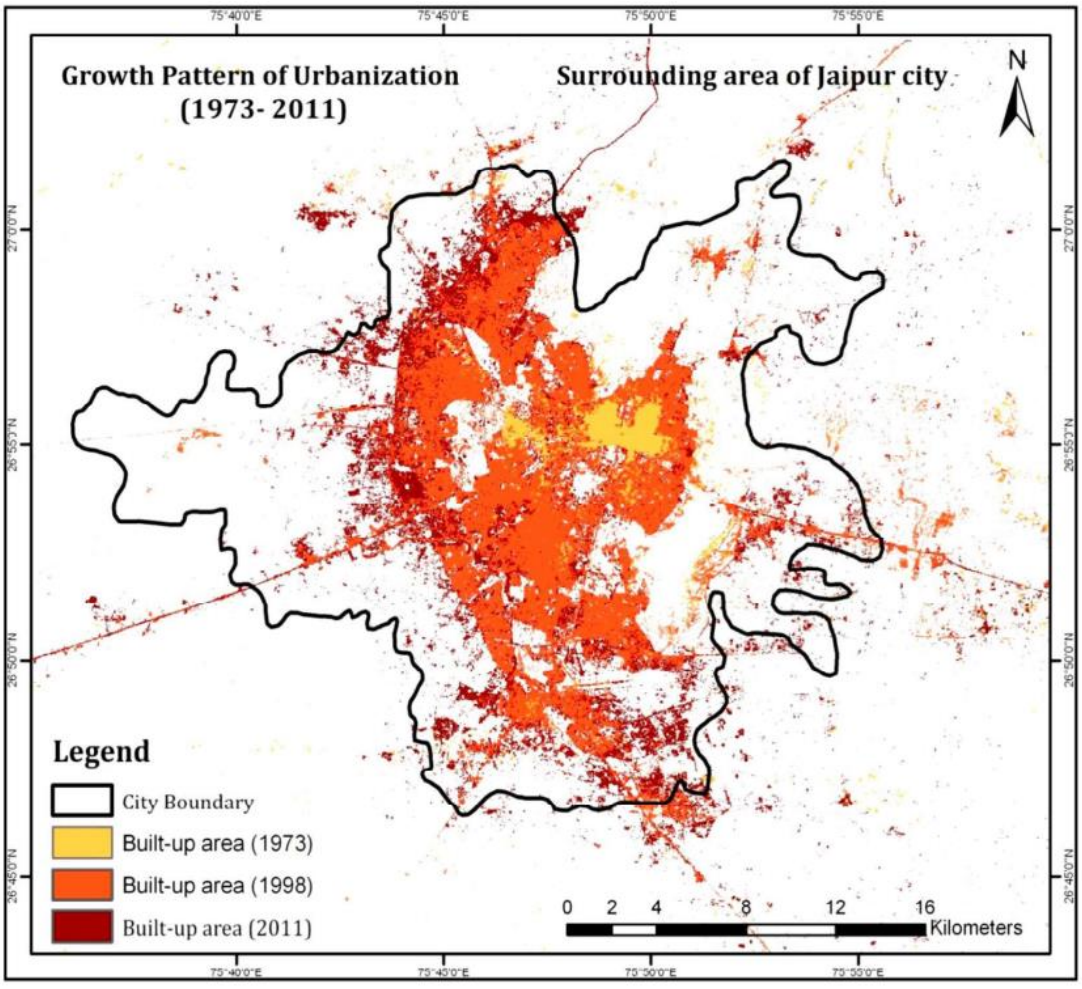


Figure 2 Urbanization pattern

` *(Rajpoot, 2014)*

3.4 TOPOGRAPHICAL FEATURES

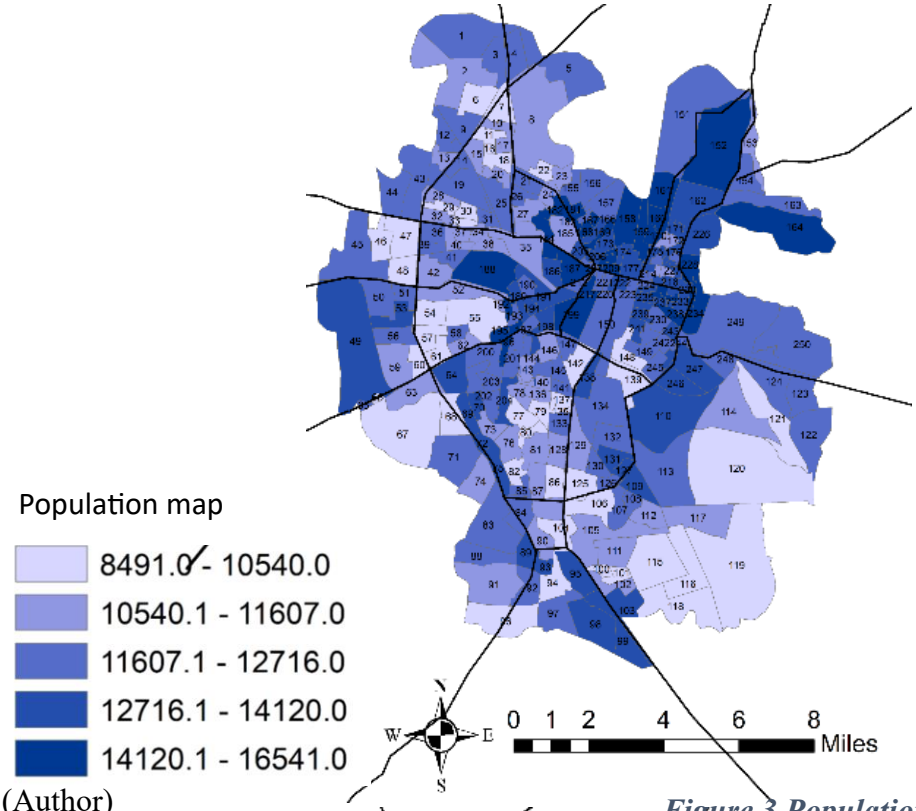
Jaipur is located at an average elevation of 431m above sea level on the eastern edge of the Thar Desert in Rajasthan. The city is surrounded on three sides by the Aravalli hills, with prominent features like Nahargarh, Jaigarh, and Amargarh fort hills providing natural protection and a scenic backdrop. Its topography slopes gently from north to south and southeast, with the Dravyavati River and seasonal streams draining the area. The landscape includes rocky outcrops, isolated hillocks such as Moti Dungri, and fertile alluvial plains towards the south and southeast. This combination of hills, plains, and river valleys shapes Jaipur's unique urban and natural environment (Corporation), 2025).

3.5 CLIMATE

Jaipur has a hot semi-arid climate, characterized by long, extremely hot summers, a short monsoon season, and mild winters (TripCrafters, 2025). Summers last from April to July, with average daily high temperatures often exceeding 40°C (104°F) (TripCrafters, 2025), and May being the hottest month. The monsoon arrives in July and continues through September, bringing most of the city's annual rainfall-about 536 to 650 mm-mainly in July and August, sometimes accompanied by thunderstorms (TripCrafters, 2025). Winters, from November to February, are mild and pleasant, with average temperatures ranging from 8°C to 22°C (46°F to 72°F), and January is typically the coldest month (TripCrafters, 2025). Humidity is generally low except during the monsoon, and the city experiences plenty of sunshine year-round (TripCrafters, 2025). The best time to visit Jaipur is during the winter months when the weather is comfortable and ideal for sightseeing (TripCrafters, 2025).

3.6 DEMOGRAPHY OF THE CITY

Jaipur, the capital of Rajasthan, is one of India's fastest-growing major cities. As of 2025, the estimated population of Jaipur city is 4,455,000. The city's population has grown steadily, rising from about 3.05 million in 2011 to over 4.4 million in 2025, reflecting an annual growth rate of around 2.93%. Jaipur's metropolitan area population is similar, as the city's urban sprawl continues to expand (India, 2025).



(Author)

Figure 3 Population 2024 map

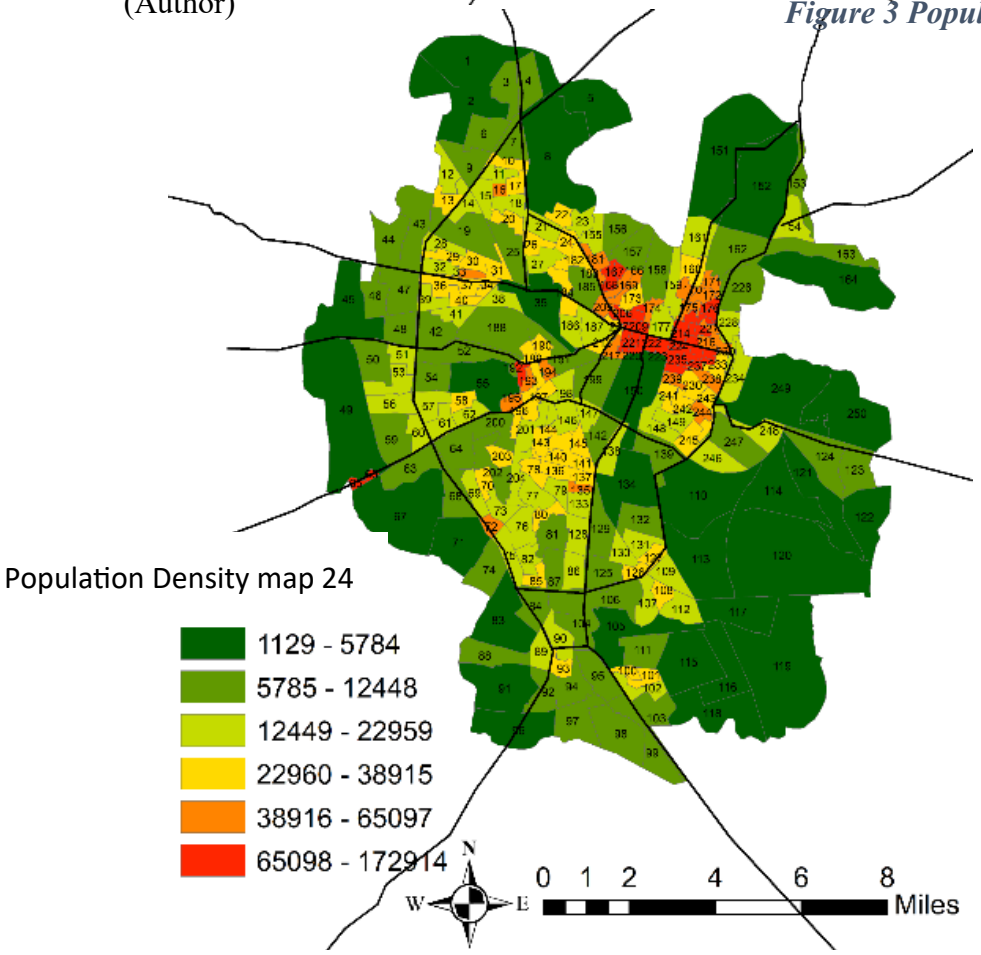


Figure 4 Population density map 2024

3.7 AIR POLLUTION IN JAIPUR

From 2011 to 2019, Jaipur experienced persistently high and, in many cases, increasing air pollution levels, particularly in its industrial and commercial zones. The main pollutants tracked were PM_{10}, SO_2, and NO_2, with PM_{10} consistently exceeding national permissible limits. (Sharma & al., 2020)

3.7.1 Air Quality Index (AQI) of Jaipur city

- The AQI was highest in western and northern Jaipur, especially at sites like Vishwakarma Industrial Area, Ajmeri Gate, Regional Office, and Jaipur Ajmer Road.
- In 2011, AQI peaked at 197 (Vishwakarma) and 161 (Regional Office).
- By 2012, AQI at the Regional Office rose to 221; Ajmeri Gate reached 192.
- The highest AQI values were observed in 2013 (Vishwakarma: 245; Ajmeri Gate: 208), and 2014 (Vishwakarma: 205; Ajmeri Gate: 190).
- From 2015–2017, AQI remained high, with peaks at the Regional Office (up to 231) and Ajmeri Gate (up to 231).
- In 2018–2019, AQI values in the most polluted areas ranged from 140 to 234.
- The lowest AQI values were consistently found in greener, less industrialized areas like Jhalana Doongri and Malaviya Industrial Area. (Mohit Jangir)

3.7.2 PM_{10} Concentrations:

- PM_{10} levels in industrial/commercial zones ranged from 216 to 295 $\mu g/m^3$ (Vishwakarma, Ajmeri Gate, Regional Office), far above the permissible limit of 60 $\mu g/m^3$.
- In southern and greener areas (Jhalana Doongri, Malaviya Industrial Area), PM_{10} was lower, generally 90–130 $\mu g/m^3$. (Mohit Jangir)

3.7.3 SO_2 and NO_2:

- SO_2 concentrations remained below the permissible limit (50 $\mu g/m^3$) at all sites, with industrial areas recording the highest values (up to 13 $\mu g/m^3$).
- NO_2 levels were highest in central and industrial areas (up to 54 $\mu g/m^3$ at the Regional Office) but generally remained within or just above national standards. (Mohit Jangir)

3.7.4 Spatial Patterns:

- The highest pollution levels were consistently recorded in the city's northern and western areas due to Urban expansion, heavy traffic, industrial emissions, and construction.
- Greener and hilly areas (Jhalana Doongri, Malaviya) benefited from natural vegetation and topography, resulting in comparatively better air quality. (Mohit Jangir)

3.7.5 Temporal Patterns:

- AQI and PM_{10} values showed fluctuations but remained high throughout the 2011–2019 period, with no clear long-term improvement.
- Occasional spikes were linked to increased industrial/commercial activity and traffic congestion.

CONCLUSION FROM THE REPORT

Jaipur's air pollution from 2011 to 2019 showed a troubling trend of persistently high AQI and PM_{10} levels, especially in industrial and commercial zones. SO_2 and NO_2 remained mostly within limits, but PM_{10} consistently exceeded safe levels. The city's rapid urbanization, industrial expansion, and vehicular growth were the main contributors. Greener and less developed areas had better air quality, highlighting the importance of urban planning, stricter emission controls, and increased green spaces to mitigate air pollution.

4. DATA COLLECTION AND ANALYSIS

4.1 LULC MAP

The LULC (Land Use Land Cover) map data for Jaipur from 1991 to 2024 shows a dramatic transformation in the city's landscape. The most notable trend is the significant increase in built-up area, which expanded from 35% in 1991 to 72% in 2024. This expansion of urban land has come at the expense of natural and open spaces:

- Hilly areas have decreased from 28% to 11%, indicating that many natural elevations have been encroached upon or developed.
- Vacant land has shrunk from 18% to 7%, suggesting that open, undeveloped spaces are rapidly being converted for urban use.

- Vegetation has declined from 16% to 7%, reflecting a substantial loss of green cover and natural habitats.
- Water bodies have remained relatively stable, fluctuating only slightly between 3% and 5%.

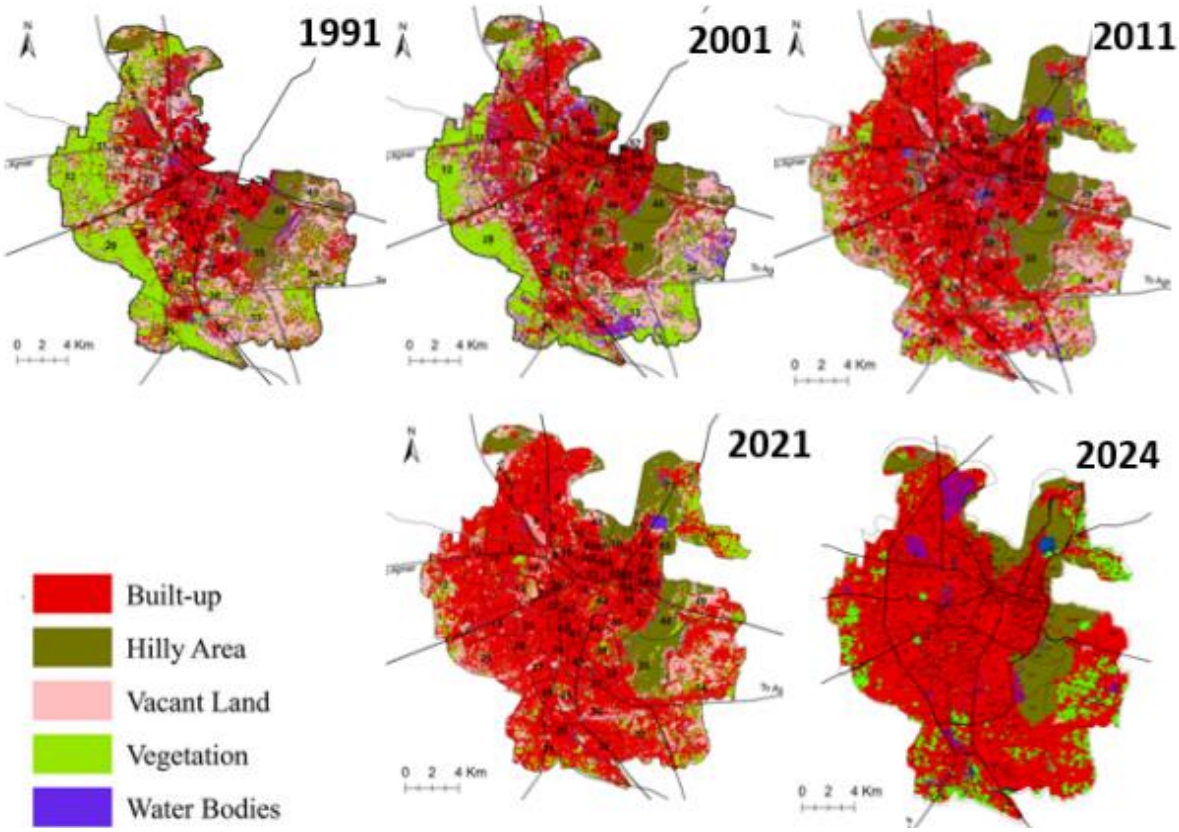
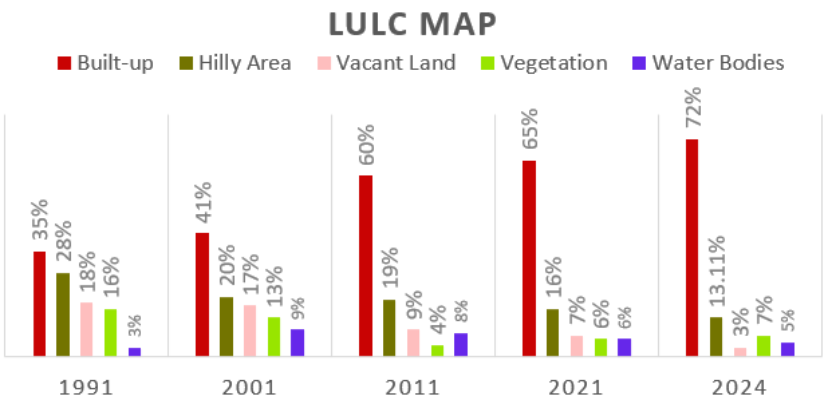
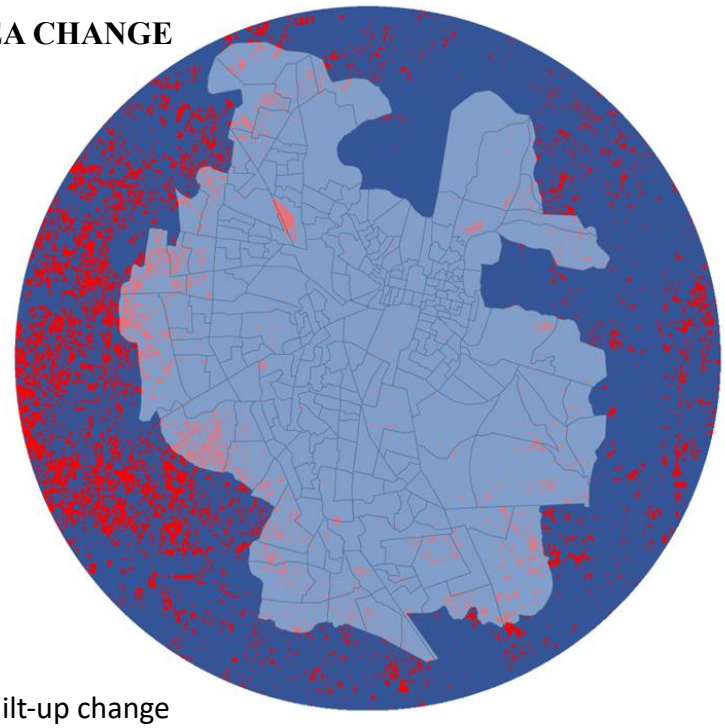


Figure 5 LULC Jaipur (1991, 2001, 2011, 2021, 2024)

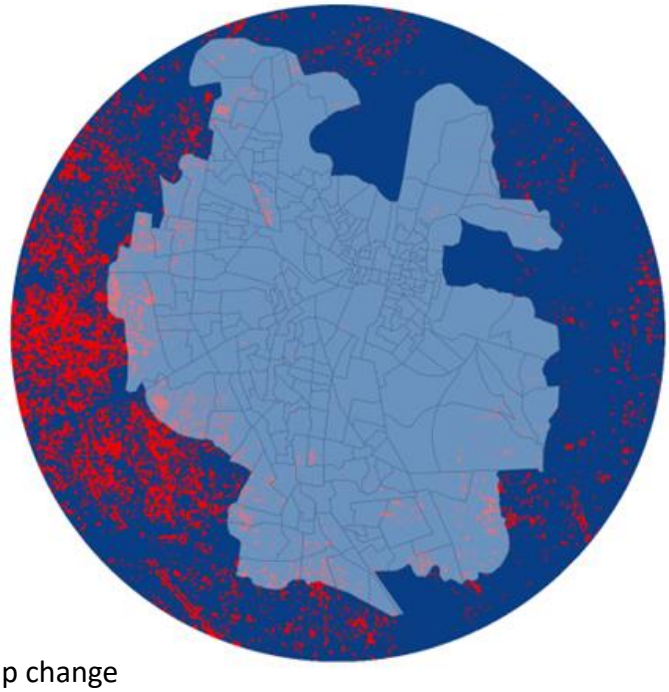
Year	City Area (sq km)	Built-up %	Built-up Area (sq km)
1991	218	35%	76.3
2001	288	41%	118.08
2011	367	60%	220.2
2021	467	65%	303.55
2024	502	72%	361.44



BUILT-UP AREA CHANGE



2001-2011 Built-up change



2001-2024 Built-up change

Figure 6 Built-up area expansion map

Overall, the LULC data highlights a clear trend of rapid urbanization, with built-up areas increasingly dominating the landscape while natural land covers-hills, vegetation, and vacant land-are steadily reduced. This shift indicates growing development pressure and poses challenges for ecological sustainability and environmental quality in Jaipur.

4.1.1 BUILT-UP AREA CHANGES ANALYSIS

Variable design and calculation

$$UEII = \frac{ULA_{i,b} - ULA_{i,a}}{t} \; x \; \frac{1}{TLA_i} \times 100$$

Variables Explained

- UEII (Urban Expansion Intensity Index)
- ULAi,a Initial urban land area at time t1.
- ULAi,b Final urban land area at time t2.
- TLAi Total land area of the city.
- Δt: Time interval in years (t2-t1).

Calculation of UEII for Jaipur city-

Total built-up area in 2011 - 220.2sqr km

Total built-up area in 2024 - 361.44sqr km

Total area of city in 2011 – 367sqr km

Total area of city in 2024 – 502sqr km

Time duration – 13year

Calculation UEII for city area – 367sqr km – 2.96

Calculation UEII for city area – 502sqr km – 2.16

Average of UEII – 2.56

Inference for Jaipur City (UEII = 2.56)

A UEII value of **2.56** places Jaipur in the "**extremely high-speed development**" category, as per established standards where:

- **>1.92** = Extremely high-speed urban expansion.

What this means:

- Jaipur has experienced urban built-up area expansion at a rate far above the typical "high-speed" threshold.
- Such a high UEII indicates very rapid and intense urbanization, with the city's built-up area increasing much faster than in most urban regions.

- This level of expansion often reflects significant land conversion from non-urban to urban use, likely driven by population growth, economic development, infrastructure projects, and increased demand for housing and services.
- While rapid expansion can stimulate economic opportunities and modernization, it also raises concerns about urban sprawl, pressure on infrastructure, environmental degradation, and the loss of green/open spaces

Classification of UEII Values

UEII categorizes expansion into 5 classes based on intensity:

UEII Range	Class	Practical Interpretation
>1.92	Very Rapid	Extreme sprawl; likely unplanned urbanization.
1.05 – 1.92	Rapid	High growth; may strain infrastructure/resources.
0.59 – 1.05	Moderate	Managed growth; balance between development & sustainability.
0.28 – 0.59	Slow	Controlled expansion; limited pressure on resources.
0 – 0.28	Very Slow	Minimal growth; possible underdevelopment or strict zoning.

Table 5 UEII range

Case Study / Title	Location / Focus
Measuring urban sprawl of small and medium towns using GIS and Expansion Intensity Index	Egypt (10 small/medium towns)
MEASURING LAND USE CHANGES AND QUANTIFYING URBAN EXPANSION IN QOM METROPOLIS, IRAN	Qom, Iran
A Case Study of the Al-Qassim Region, Saudi Arabia	Al-Qassim, Saudi Arabia
Assessment of urban growth in relation to urban sprawl using UEII standards	International (Comparative)
Quantifying urban expansion and its driving forces in Chengdu	Chengdu, China

Table 6 Case studies who used UEII

These studies use the same standard UEII classification (Ren et al., 2013), ensuring comparability of results across different regions and research

4.2 LAND-USE MAP

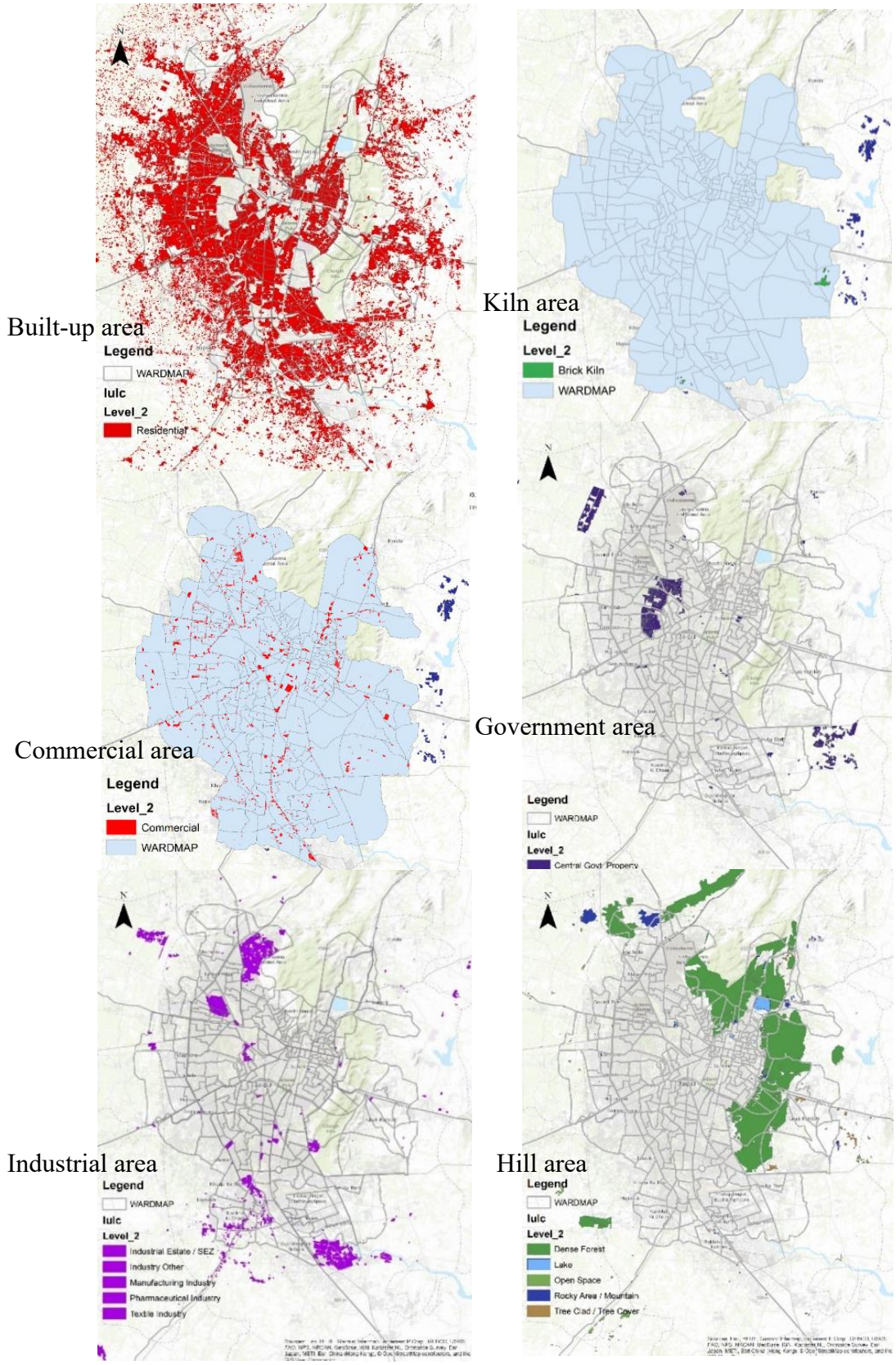


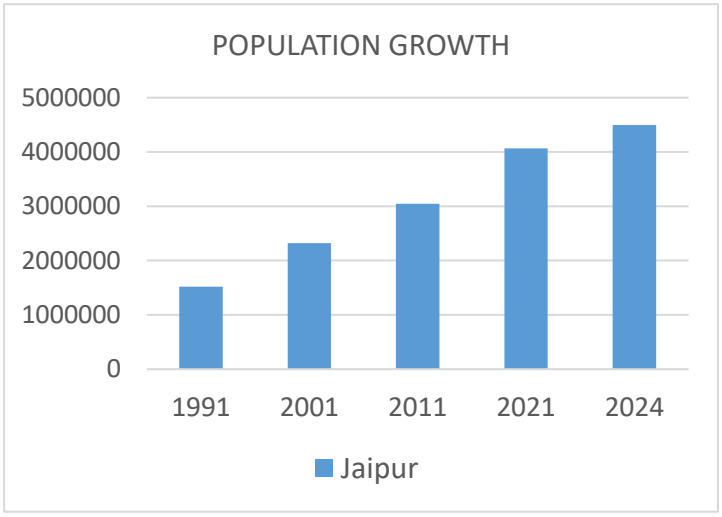
Figure 7 Land-Use maps

These land-use maps illustrate the diverse patterns of land utilization across Jaipur city, clearly indicating the location and extent of residential, commercial, industrial, Road network, Open space, green areas, and vacant areas. By visually representing how different parts of the city are allocated for various uses, these maps provide valuable insights into the dynamics of urban growth. Understanding these spatial patterns is essential for analysing how urban expansion influences air quality, as changes in land use-such as the conversion of green spaces to built-up or industrial areas-can significantly affect pollution levels.

4.3 POPULATION GROWTH & DENSITY

4.3.1 POPULATION GROWTH

The population graph reveals that Jaipur's population has nearly tripled, rising from about 1.5 million in 1991 to over 4.5 million in 2024. This population boom has paralleled and fuelled the city's spatial expansion and intensification of development.



4.3.2 POPULATION DENSITY DISTRIBUTION (2024)

The second map provides a detailed view of Jaipur's population density for 2024. The highest densities (dark red and orange, 39,000–172,914 people/sq. Km) are concentrated in the city centre and surrounding older neighbourhoods, reflecting historic urban cores and commercial area. Intermediate wards (yellow and light green, 5,785–38,915 people/sq. Km) form a transitional ring between the dense core and the outskirts. The lowest densities (dark green, 1,129–5,784 people/sq Km) are found on the city's periphery, where newer development, open land, and natural features like hills predominate.

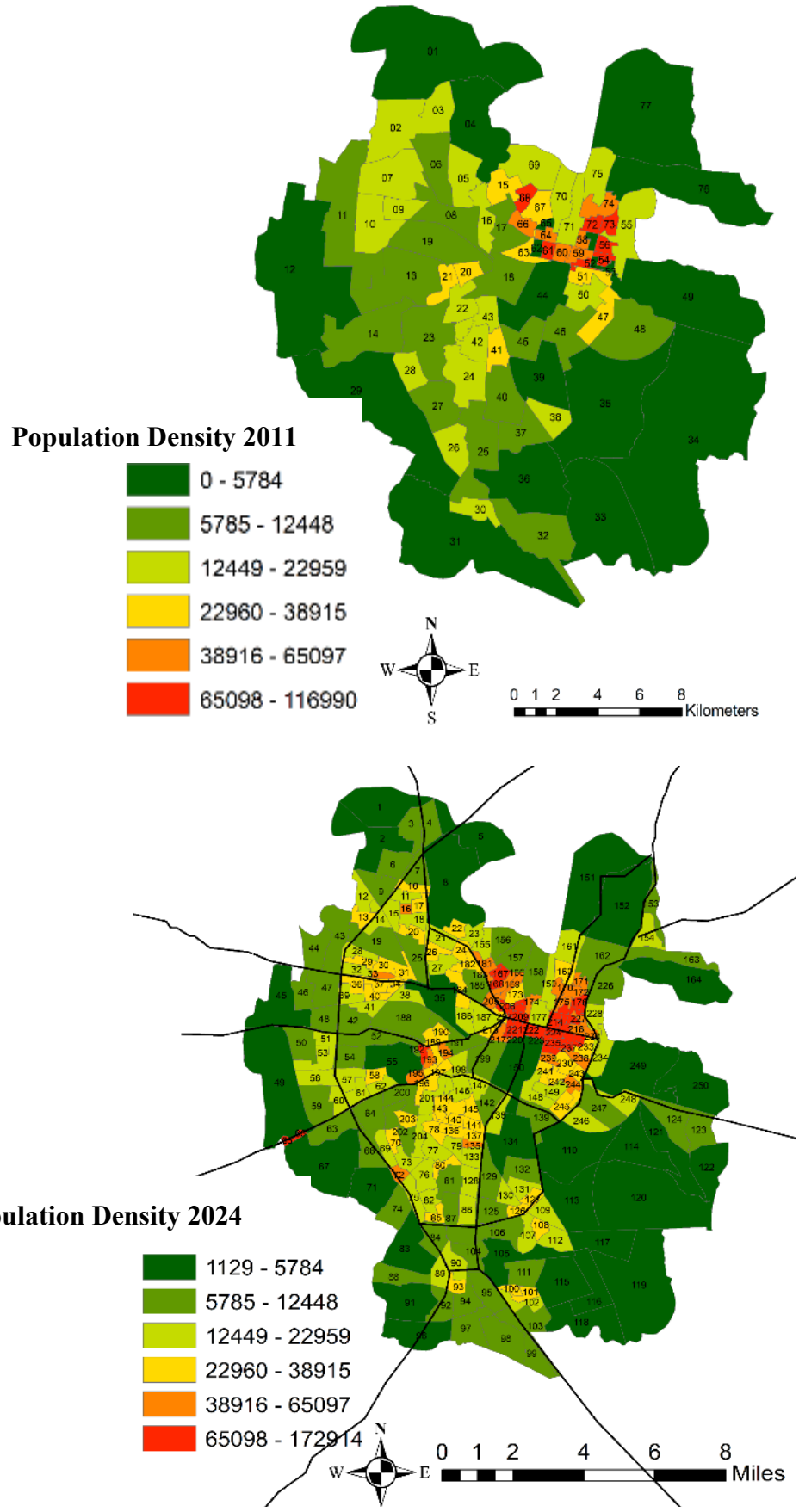
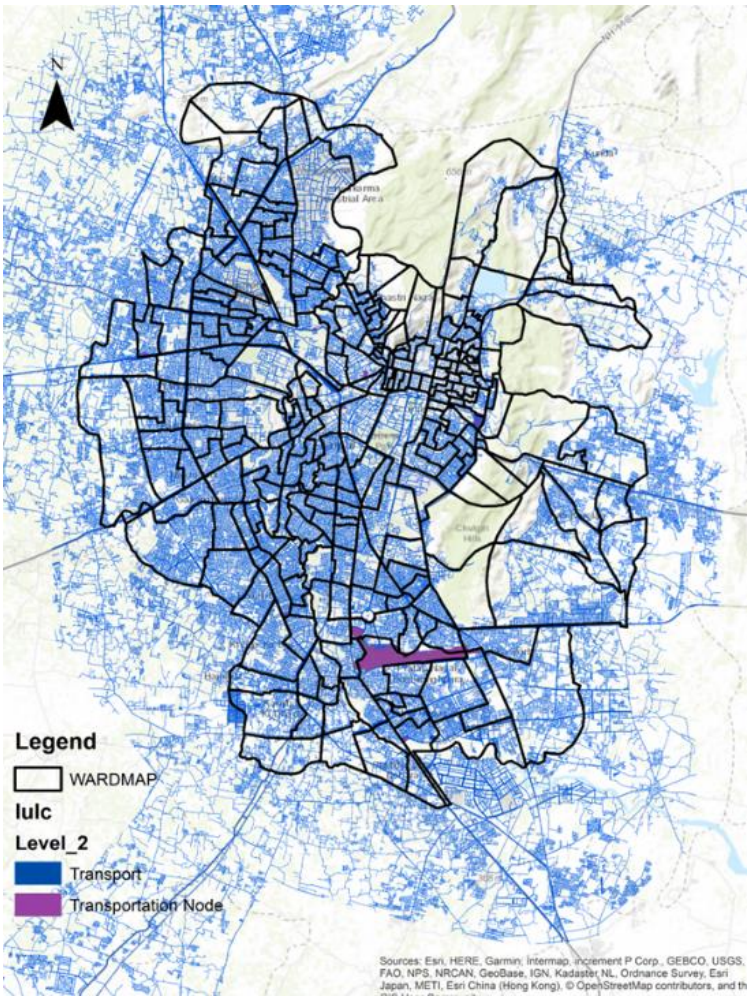


Figure 8 Population density map 2011 & 2024

INTEGRATED INTERPRETATION

- Jaipur has experienced **explosive urban growth**, with built-up land expanding fivefold and city area more than doubling in three decades.
- This expansion has come at a **significant environmental cost**, as natural land covers-hills, vegetation, and vacant land-have been steadily reduced.
- The **population has nearly tripled**, intensifying pressure on land, infrastructure, and resources.
- **Population density** is highest in the historic core and older neighborhoods, tapering off towards the city's edge, a classic pattern of urban sprawl and outward expansion.
- These trends highlight urgent challenges for sustainable urban planning, preservation of green spaces, and the need to balance growth with environmental resilience and quality of life.

4.3.3 ROAD NETWORK AND ROAD DENSITY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Level_2
Transport
Transportation Node
Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), © OpenStreetMap contributors, and th

Figure 9 Road network map

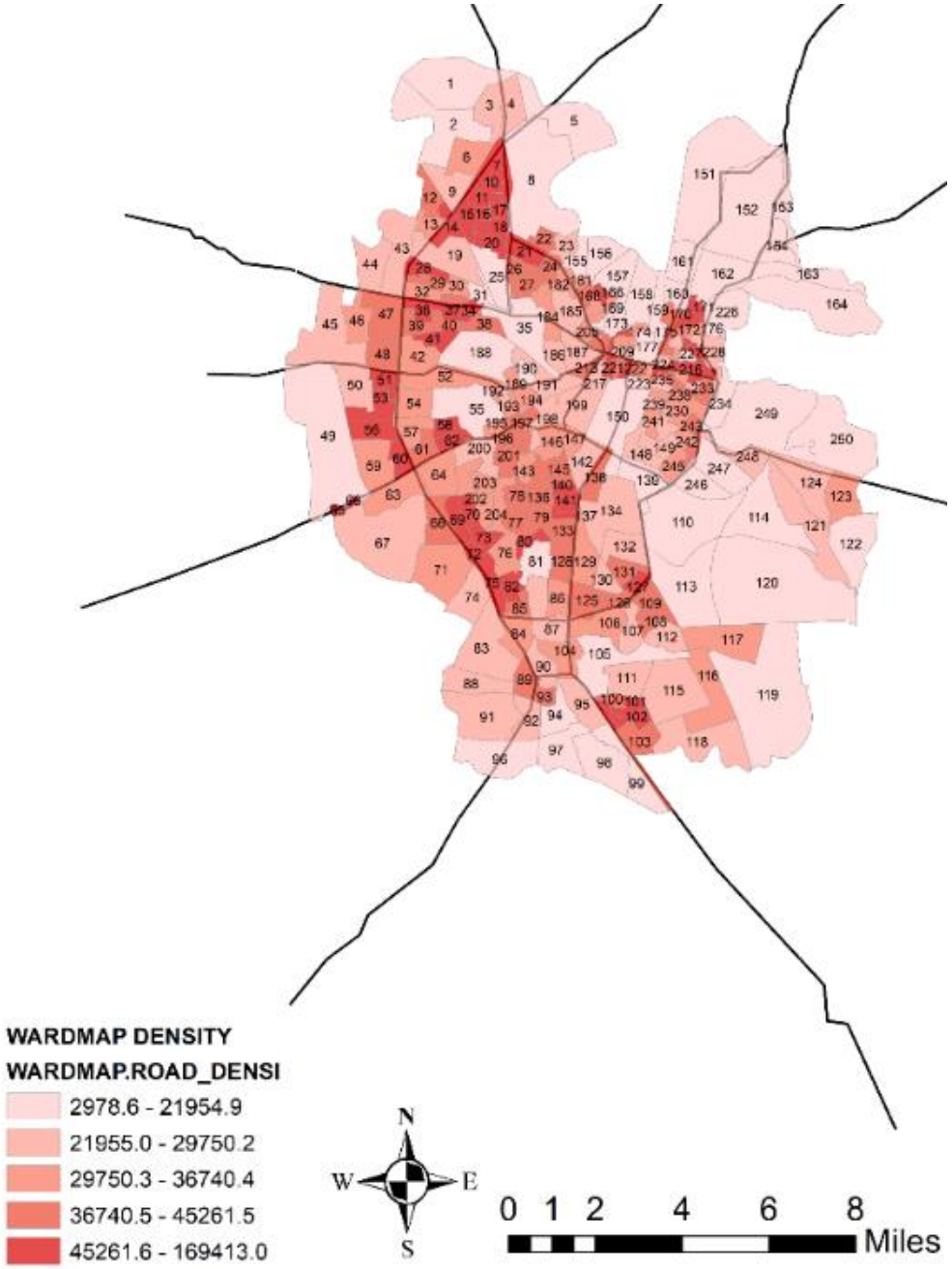


Figure 10 Road Network map

This spatial distribution of road density correlates strongly with urban growth patterns in Jaipur, where historically the central wards have been the hub of commercial, residential, and institutional development. Higher road density is both a driver and consequence of urban expansion, facilitating mobility, land development, and densification. As Jaipur grows, particularly through infill development and outward sprawl, the road network plays a critical role in shaping land use and accessibility. The expansion of road infrastructure into peripheral wards suggests ongoing urban sprawl, while high-density central areas reflect mature urban cores undergoing intensification.

4.4 EMISSION CONTRIBUTION BY SECTORS

The data visualizes emission contributions by sector for particulate matter (PM) in Jaipur. For PM10, road dust is the dominant contributor at 47% (75,409 units), followed by mineral mines (14%, 22,380 units), brick kilns (7%, 11,926 units), and construction activities (7%, 11,640 units). The PM10 total reaches 160,452 units across all sources (Sharma & al., 2020).

For PM2.5, which poses greater health risks due to smaller particle size, road dust remains the largest contributor at 36% (18,244 units), but vehicles (15%, 7,863 units), industry (15%, 7,799 units), and domestic sources (14%, 7,190 units) play more significant roles. The PM2.5 total is 51,233 units (Sharma & al., 2020).

This analysis reveals that Jaipur's air pollution is primarily caused by infrastructure-related issues like unpaved or poorly maintained roads, followed by industrial activities and transportation. The data highlights the need for targeted interventions in road management, industrial emissions control, and vehicle regulations to effectively address Jaipur's air quality challenges (Sharma & al., 2020).

Figure 11 Road condition picture

EMISSION CONTRIBUTION BY SECTORS

Sources	PM10	PM2.5
Road Dust	75409	18244
Mineral Mines	22380	2239
Brick kiln	11926	1314
Construction & Demolition	11640	2677
Domestic	10040	7190
Vehicle	8737	7863
Industry	8666	7799
Stone Crusher	7009	734
MSW Burning	2732	1858
Hotels and Restaurants	1172	727
DG Sets (Industry)	427	384
Banquet Hall	255	150
Hospitals	21	19
Apartments	7	7
Total	160452	51233

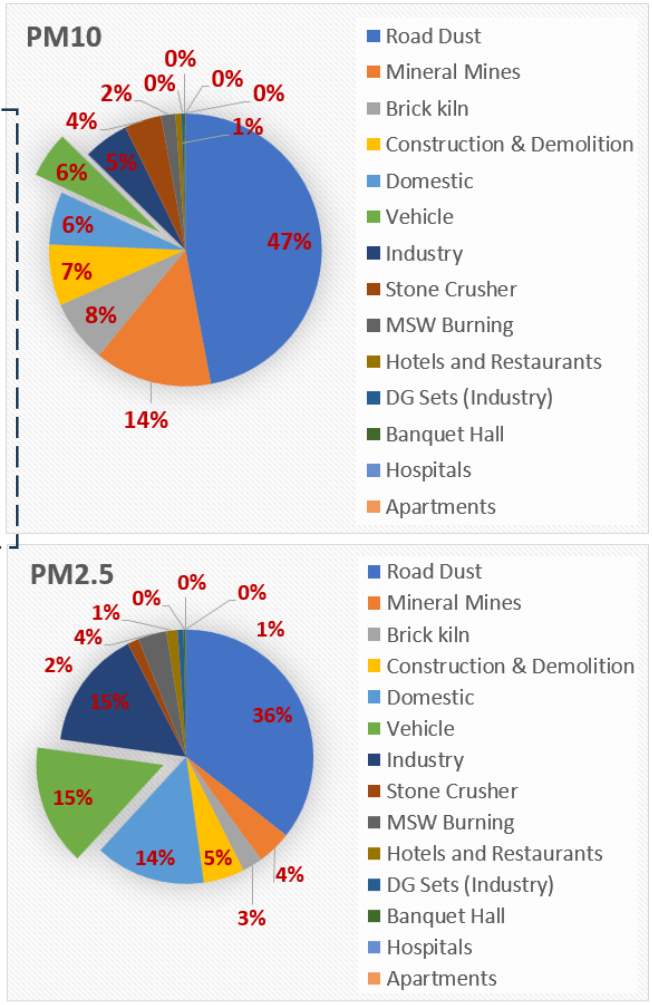


Table 7 Emission contribution by sectors *(Sharma & al., 2020)*

Figure 12 Industry, Road condition & Road side Parking

4.4.1 AIR QUALITY (ANNUAL COMPARISON)

- **AQI 2000**: Shows values ranging from 45.8 to 55.5, with higher concentrations (orange-red) in central and western parts of the city
- **AQI 2023**: Shows increased values ranging from 51.5 to 68.4, with expanded areas of poor air quality
- **AQI Change**: Shows increases of 1.4 to 14.1 units across most of the city, indicating worsening air quality

COMPARISON WITH WHO STANDARDS

The 2021 WHO Air Quality Guidelines significantly lowered the recommended annual mean PM2.5 concentration from 10 µg/m³ to 5 µg/m³ (Organization, 2021), reflecting the serious health impacts of air pollution even at lower levels. AQI values rather than direct PM2.5 measurements, research indicates:

- Even the lowest AQI values shown (45.8 in 2000 and 51.5 in 2023) strongly suggest PM2.5 concentrations far exceeding the WHO guideline of 5µg/m³
- The visible increase in AQI values from 2000 to 2023 indicates Jaipur's air quality is moving further away from, rather than toward, the WHO recommendations

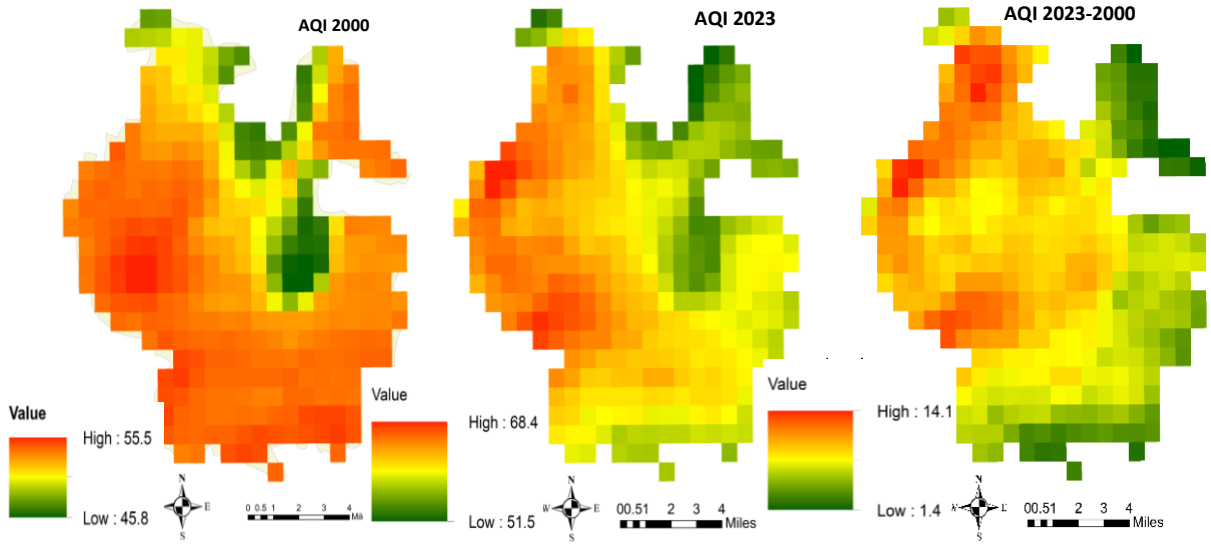


Figure 13 Annual AQI Difference (2023 & 2000)

4.4.2 AIR QUALITY (SEASONAL COMPARISON)

A comparative analysis of air pollution (likely PM2.5 or PM10 concentrations) in Jaipur across three representative months-April, August, and December-for the years 2000 and 2023, along with the absolute change between these years.

KEY OBSERVATIONS

- **Overall Increase in Pollution Levels:** Across all months, the pollution values (indicated by the color scale from green [low] to red [high]) are higher in 2023 compared to 2000. The upper value ranges have shifted upward, with maximum readings rising from 55.1 (April 2000) to 66.5 (April 2023), 28.1 (August 2000) to 94.4 (August 2023), and 61.2 (December 2000) to 98.1 (December 2023).

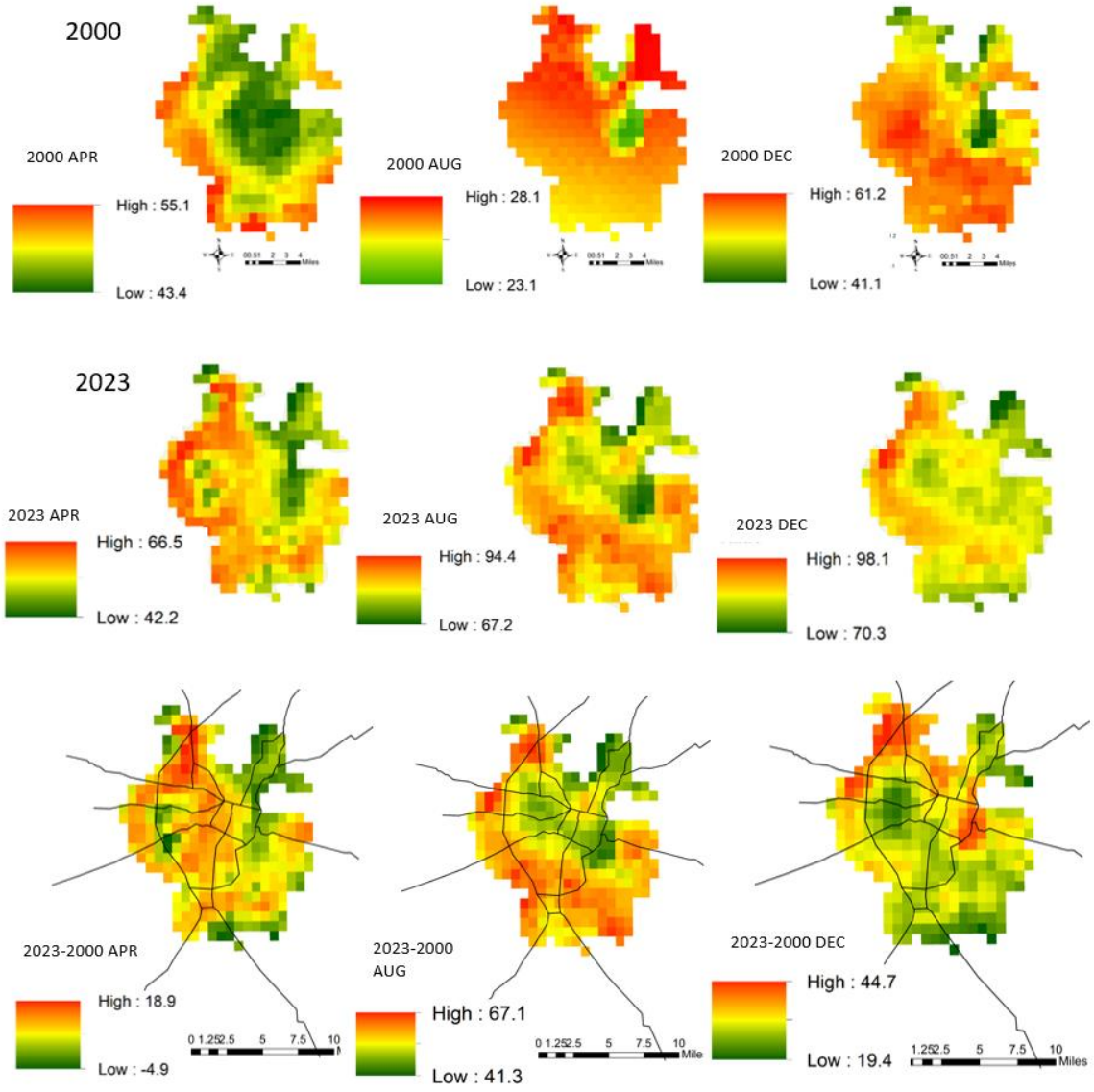


Figure 14 Seasonal AQI comparison (2023 & 2000)

INTERPRETATION

- **Rising Baseline Pollution:** The city's baseline pollution has increased significantly over two decades, with the most dramatic rise in the monsoon (August), indicating that pollution sources now outweigh seasonal cleansing effects.
- **Worsening Winter Episodes:** December's sharp rise highlights growing wintertime air quality crises, likely due to increased emissions, temperature inversions, and stagnant atmospheric conditions.
- **Urban Growth Correlation:** The areas with the largest pollution increase align with zones of urban expansion and densification, reflecting the impact of population growth, vehicular traffic, and construction.

4.5 AIR QUALITY ANALYSIS

4.5.1 ANNUAL AQI TREND (OVERALL CHANGE)

From the first image:

- **2000 Average AQI**: 50.65 (midpoint of 45.8–55.5)
- **2023 Average AQI**: 59.75 (midpoint of 51.5–68.4)
- **Change**:

$$\Delta \text{AQI}_{\text{annual}} = 59.75 - 50.65 = +9.1$$

INTERPRETATION

Overall, AQI increased by 9.1 units from 2000 to 2023, indicating worsening air quality city-wide.

4.5.2 SEASONAL TREND ANALYSIS

SEASONAL VARIATION

- April: Both years show moderate pollution, but 2023 has more widespread high values (more yellow/orange).
- August: In 2000, August had the lowest values (monsoon effect), but by 2023, pollution is much higher and more uniformly distributed, suggesting diminished monsoon cleansing or increased year-round emissions.
- December: Both years show high pollution, but 2023 is much worse, with the highest values and more extensive orange/red areas, indicating severe winter pollution episodes.

- Spatial Patterns: In all months, the central and northern parts of Jaipur tend to have higher pollution, with the worst increases in these zones from 2000 to 2023.
- Change Maps (Bottom Row): The difference maps (2023 minus 2000) show the greatest increases in August (up to +67.1 units), followed by December (+44.7) and April (+18.9). The spatial spread of increased pollution is citywide but most pronounced in central and northern sectors.

➢ **MONSOON (AUG) COMPARISON**

From second image:

- **2000 AUG AQI**: High = 28.1, Low = 23.1 ⇒ Average 25.6
- **2023 AUG AQI**: High = 94.4, Low = 67.2 ⇒ Average 80.8
- **Change**:

$\Delta AQI\ Aug = 80.8 - 25.6 = +55.2$

INTERPRETATION

Massive increase in AQI during monsoon, likely due to high humidity inhibiting pollutant dispersion and increased emissions.

➢ **WINTER (DEC) COMPARISON**

From second image:

- **2000 DEC AQI**: High = 61.2, Low = 41.1 ⇒ Average 51.2
- **2023 DEC AQI**: High = 98.1, Low = 70.3 ⇒ Average 84.2
- **Change**:

$\Delta AQI\ Dec = 84.2 - 51.2 = +33.0$

INTERPRETATION

Significant AQI rise in winter, consistent with poor dispersion due to temperature inversion and emissions from heating or traffic.

➢ **SPRING (APR) COMPARISON**

- **2000 APR AQI**: High = 55.1, Low = 43.4 ⇒ Avg 49.3
- **2023 APR AQI**: High = 66.5, Low = 42.2 ⇒ Avg 54.4
- **Change**:

$\Delta AQI\ Apr = 54.4 - 49.3 = +5.1$

INTERPRETATION

AQI increased moderately in spring. Less drastic compared to monsoon and winter.

Season/Period	2000 AQI (Avg)	2023 AQI (Avg)	Change	Trend
Annual (General)	50.65	59.75	**+9.1**	Moderate deterioration
April (Spring)	49.3	54.4	**+5.1**	Slight increase
August (Monsoon)	25.6	80.8	**+55.2**	Severe deterioration
December (Winter)	51.2	84.2	**+33.0**	Strong deterioration

Table 8 Interpretation of Season AQI change

INSIGHTS

- **Monsoon** shows the **highest rise** in AQI (+55), possibly due to increased vehicular emissions, construction, and stagnant air.
- **Winter** follows, consistent with typical seasonal inversion.
- **Annual trend** shows consistent urban air degradation.
- Likely driven by **urban growth**, **increased traffic**, **reduced vegetation**, and **industrialization**.

4.6 LST MAP ANALYSIS

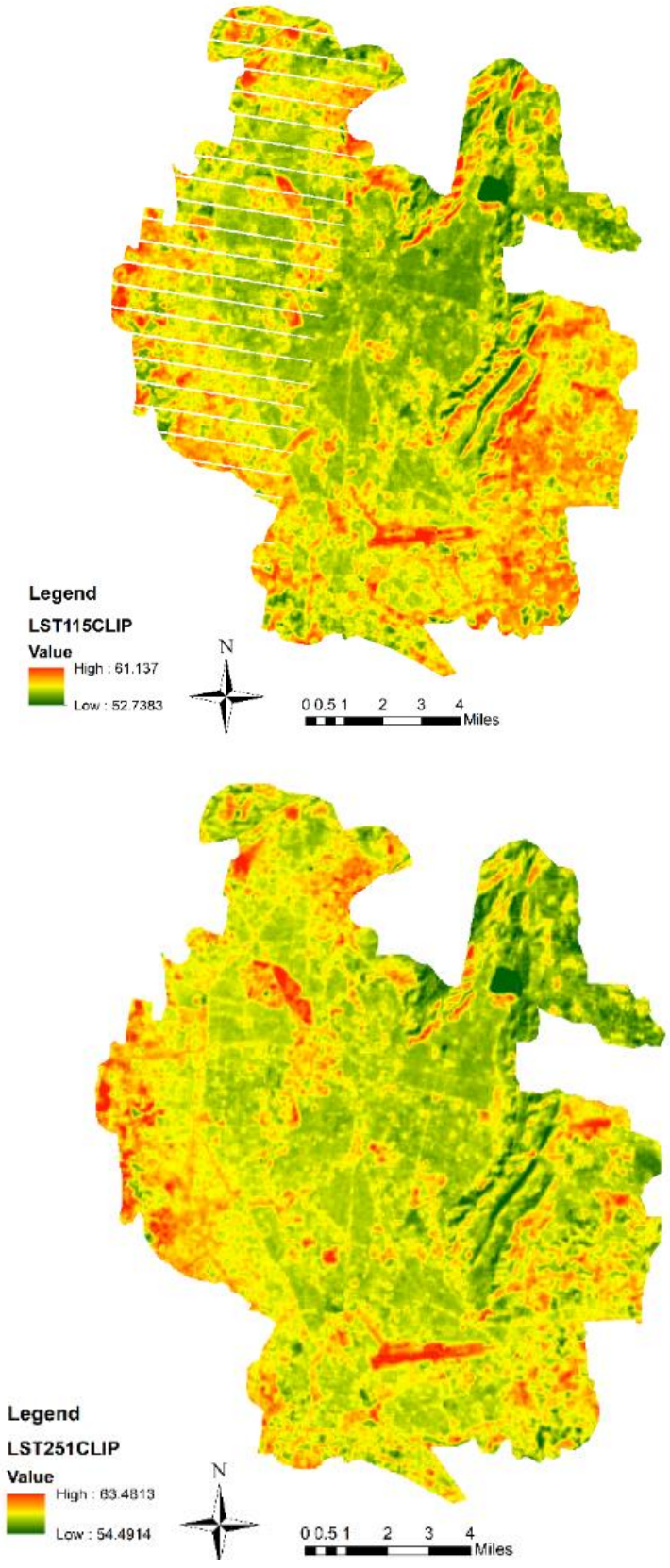


Figure 15 LST map (2015 & 2025)

The LST (Land Surface Temperature) map shown the spatial distribution of surface temperatures across Jaipur city.

- The left map (2015) shows temperature values ranging from 52.7383° (low) to 61.137° (high)
- The right map (2025) shows higher temperature values ranging from 54.4914° (low) to 63.4813° (high)

These maps illustrate Jaipur's urban heat profile, showing how temperatures vary across different parts of the city. Several key patterns are evident:

1. There's a clear temperature gradient across Jaipur, with central and western parts of the city (shown in yellow, orange, and red) experiencing higher surface temperatures compared to the greener eastern and central portions (shown in green).
2. The higher temperatures align with industrial areas and densely built-up regions of Jaipur, while lower temperatures correspond with areas having more vegetation coverage or water bodies (such as around Jal Mahal).
3. The difference between the two maps suggests a temporal increase in surface temperatures, with the maximum temperature rising by approximately 2.3° (from 61.1° to 63.5°).

This visualization supports research findings that Jaipur experiences significant urban heat island effects, with temperature variations of around 8° across the city. The elevated temperatures in built-up areas reflect the city's rapid urbanization, where vegetation and open spaces have been replaced by construction and development, affecting the city's microclimate.

4.7 GIS LAYERS AND ANALYTICAL PURPOSE

City / Region	Study Title	Methods Used	Key Findings
Chengdu, China	Spatiotemporal heterogeneities and drivers of air pollution in Chinese megacity: a case study of Chengdu	GWR, LMDI, Gi* hotspot analysis	Identified spatial heterogeneity in air pollution drivers; urbanization and green space coverage significantly influenced AQI variations.
Surabaya, Indonesia	Comparison of Spatial Modelling Approaches on PM10 and NO2 Concentration Variations	GWR, GTWR, LUR	GWR and GTWR outperformed LUR in capturing spatial variability of PM10 and NO2; highlighted the importance of spatial-temporal modeling in urban air quality assessment.
Beijing, China	Spatiotemporal Analysis of Air Quality and Its Driving Factors in Beijing's Main Urban Area	GWR, MGWR, Moran's I	Demonstrated spatial heterogeneity in AQI drivers; MGWR provided nuanced insights into variable influences across different urban areas.
Tehran, Iran	Spatial Modeling of Air Pollutant Concentrations Using GWR and ANFIS Models	GWR, ANFIS	Achieved high model accuracy ($R^2 > 0.82$) in predicting PM2.5 and CO concentrations; traffic density identified as a significant predictor of air pollution levels.
Bangladesh	A Multivariate Geostatistical Framework to Assess the Spatio-Temporal Dynamics of Air Pollution and Land Surface Temperature	GWR, Moran's I	Found significant high-high clusters of NO_2 and O_3 concentrations; over 30% of the area exhibited substantial pollution hotspots, correlating with land surface temperature variations.
Jeddah, Saudi Arabia	Modeling Spatial Distribution and Determinant of PM2.5 at Micro-Level Using Geographically Weighted Regression	GWR	Identified spatial variability in PM2.5 concentrations across campus areas; findings informed sustainable mobility policies and campus planning.
Kolkata, India	Hotspot Detection, Traffic Pollution and Asthma Incidence in and around Kolkata, India	Hotspot analysis, GIS mapping	Detected significant hotspots of PM10 and NO2 concentrations; established correlation between traffic-related air pollution and increased asthma incidence among children.

Table 9 Case studies that used GWR and Hotspot Analysis

To understand the spatial dynamics of air pollution in relation to urban growth, a series of GIS-based thematic maps were developed using multiple input layers such as AQI, population density, road density, and sprawl index. These maps form the backbone of the spatial analysis, allowing for both correlation modelling and identification of high-risk zones. The purpose of these maps is to quantify and visualize the relationship between urban form and air quality across Jaipur city. By employing techniques such as Geographically Weighted Regression (GWR) and hotspot analysis, the maps enable localized understanding of how variables like road infrastructure and urban sprawl influence air pollution. The following table summarizes each map, the layers used to generate them, and their specific analytical contribution to the study.

4.8 INTERPRETATION OF MAPS

Map Title	Input Layers	Methodology / Tool	Purpose / Interpretation
AQI 2023 Hotspot Map	AQI point data (2023)	Getis-Ord Gi* statistic (1000 m fixed distance)	Identifies statistically significant clusters of high and low air pollution levels across Jaipur.
Road Density R^2 Map	Road density raster, AQI data	GWR analysis	Maps where AQI is most influenced by road infrastructure and traffic volume.
Sprawl R^2 Map	Sprawl index, AQI data	GWR analysis	Shows spatial correlation between urban sprawl patterns and AQI.
Sprawl Index Hotspot Map	Composite index of road + population density	Getis-Ord Gi* statistic	Highlights clusters of high urban sprawl, which tend to correlate with AQI hotspots.
Max R^2 (P vs. R) Map	GWR R^2 values (population vs. road density)	Conditional selection of max R^2 values	Identifies which factor (population or road density) better explains AQI in each grid cell.
Max R^2 Hotspot Map	Highest local R^2 values from GWR	Getis-Ord Gi* statistic	Detects zones where urban growth factors most strongly influence air quality.
Composite Sprawl Index Map	Population density, road density	Normalization + raster calculator (composite)	Generates a spatial measure of urban sprawl for use in correlation and hotspot analysis.
Built-up Area Change Map	LULC raster maps (2005, 2015, 2025)	Raster reclassify + change detection	Assesses spatial and temporal changes in built-up areas as a result of urban expansion.

Table 10 Interpretation of Maps

4.9 EXPANSION OF BUILT-UP AREA

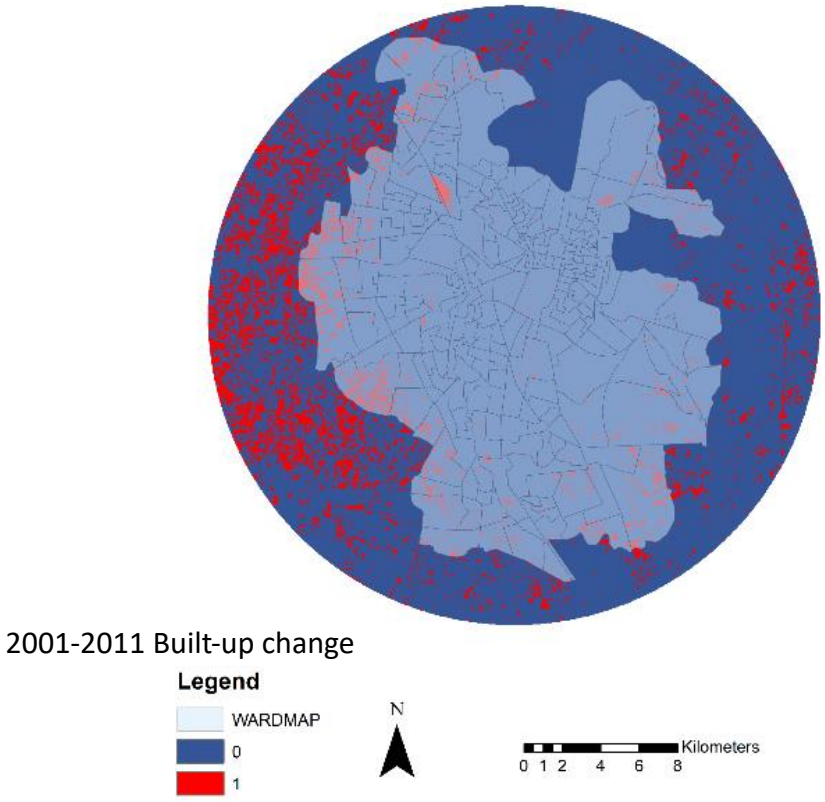


Figure 16 Built-Up area change (2001-2011)

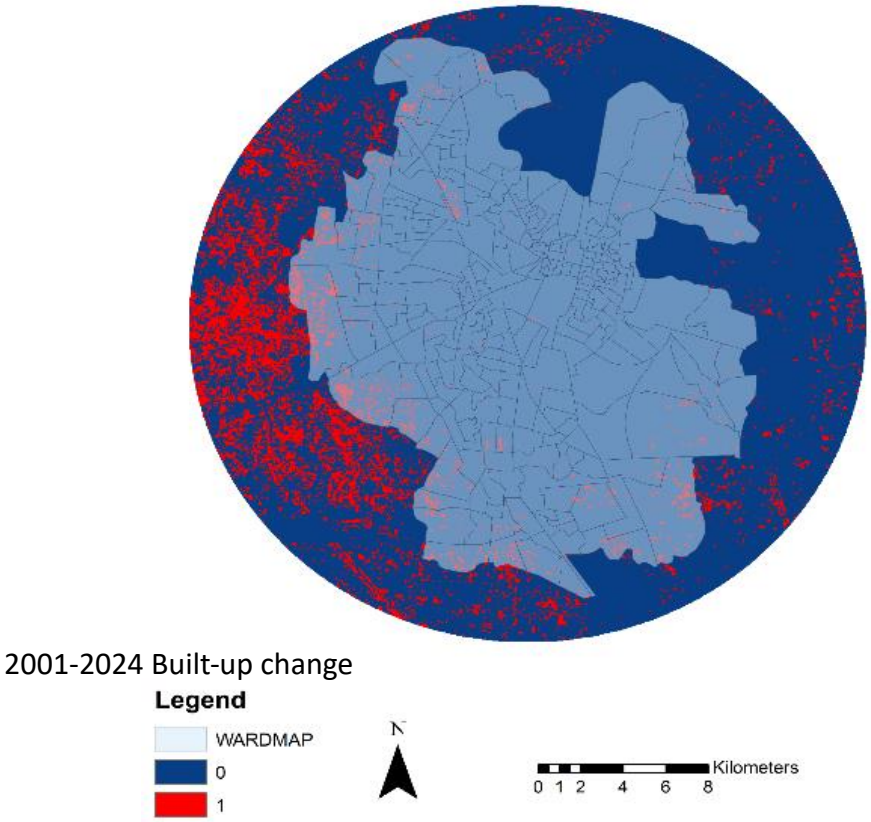


Figure 17 Built-up area change (2001-2024)

The maps above illustrate the spatial dynamics of built-up area expansion in Jaipur city between 2001–2011 and 2001–2024. The analysis reveals a pronounced trend of urban sprawl, particularly towards the western periphery of the city. Over these two decades, significant new built-up development (shown in red) has occurred mainly in the western zones, reflecting the outward expansion of Jaipur's urban footprint (Gupta, 2011). This pattern is consistent with previous studies indicating that natural barriers, such as hills to the north and east, have constrained growth, channeling it towards the west and south (Gupta, 2011).

Recent air quality data and spatial analyses further indicate that this sprawling urban growth in the western part of Jaipur is associated with a rise in air pollution levels (AQI) in the same region (Suman Sharma, 2024). The increase in built-up areas leads to higher vehicular emissions, more dust from construction, and reduced green cover, all contributing to deteriorating air quality. As a result, the western periphery—where urban expansion is most rapid—is also experiencing some of the highest AQI readings in the city, highlighting the environmental impact of unchecked urban sprawl on public health and urban sustainability (Suman Sharma, 2024).

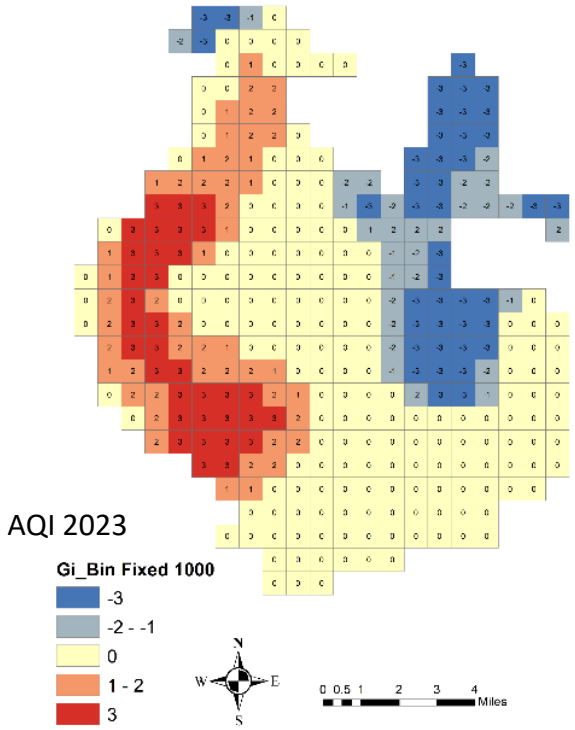


Figure 19 AQI Hotspot analysis map

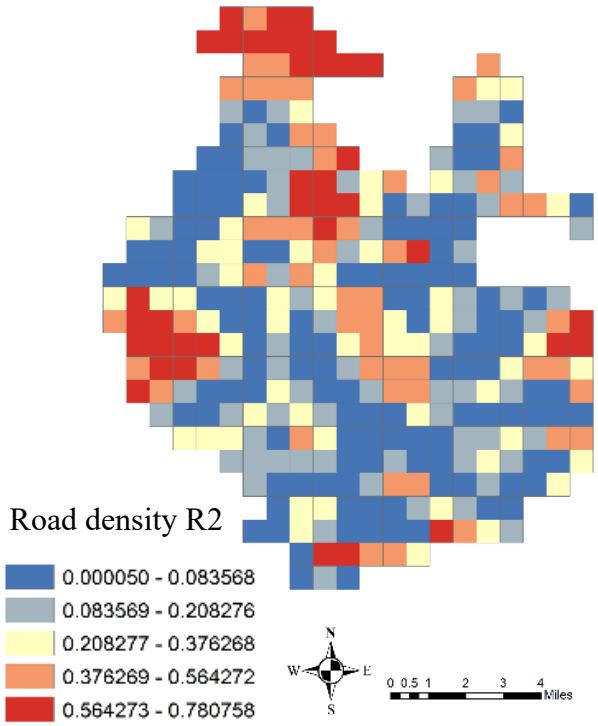


Figure 18 Road density R2 map

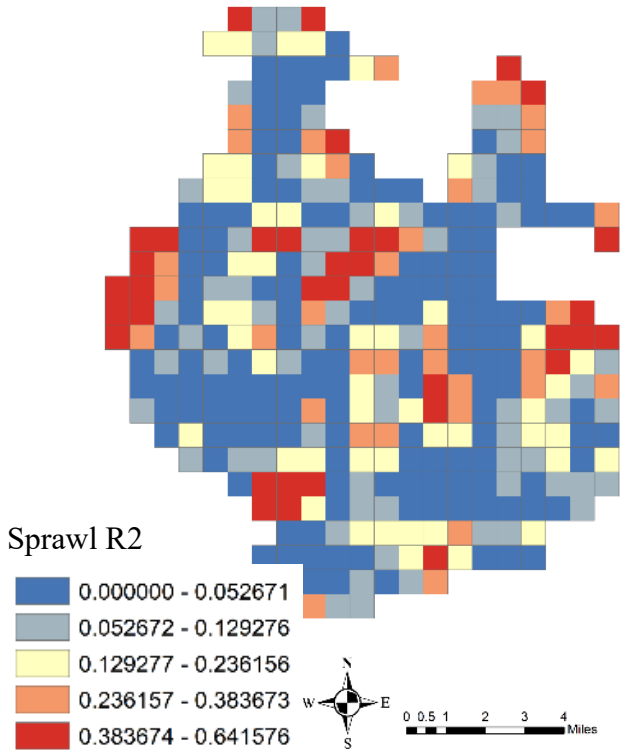


Figure 20 Sprawl R2 map

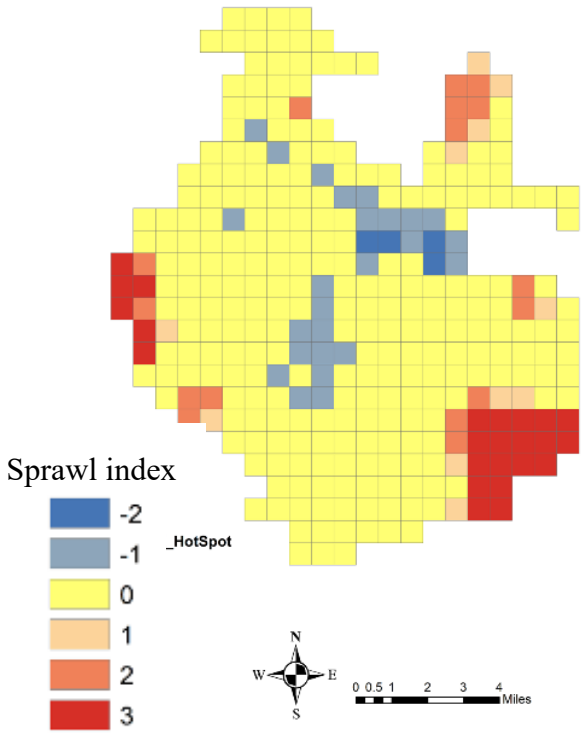


Figure 21 Sprawl Index (Hotspot analysis) map

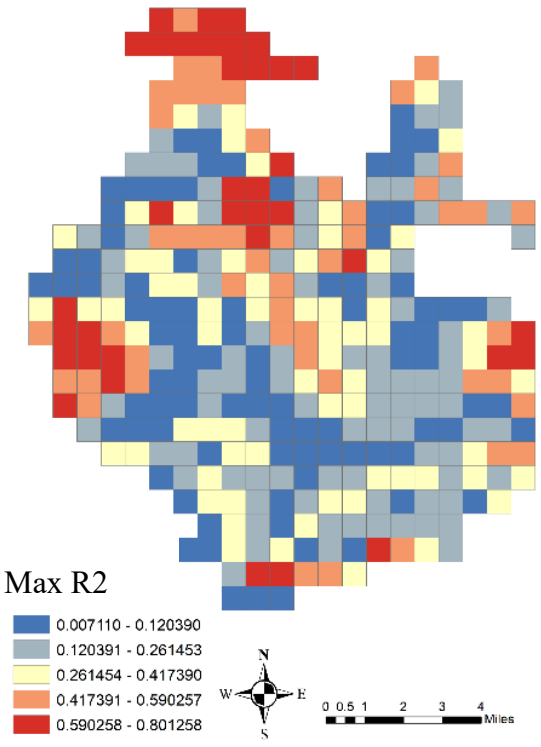


Figure 23 MAX R2 map

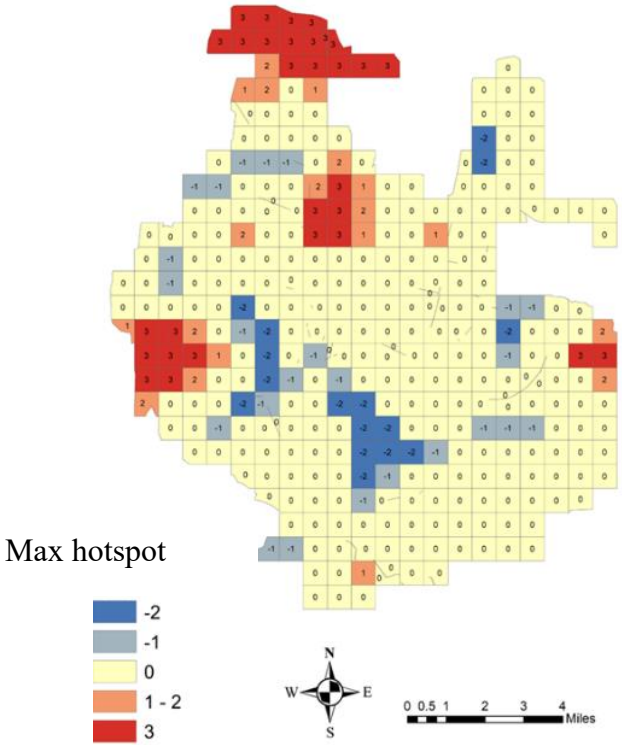


Figure 22 MAX Hotspot analysis map

4.9.1 GWR AND HOTSPOT MAPPING OF URBAN GROWTH–AIR QUALITY

To investigate the spatial correlation between urban growth and air quality degradation in Jaipur city, a multi-layered geospatial analysis was conducted using **Geographically Weighted Regression (GWR)** and *hotspot detection with Gi statistics** in ArcGIS. The aim was to identify areas where air quality (measured through AQI) is significantly influenced by variables such as road density, population density, and urban sprawl. A 1 km × 1 km fishnet grid was used to standardize spatial units, ensuring consistent comparison across the study area. Local R^2 values from GWR were mapped to show the explanatory power of predictor variables, while Gi* statistics were applied to detect statistically significant spatial clusters.

INTERPRETATION OF RESULTS

The **AQI Hotspot Map (2023)**, categorized using Gi* statistic with a fixed distance band of 1000 meters, highlights statistically significant clusters of poor air quality across the city. Red areas represent AQI hotspots (with 95–99% confidence), mostly concentrated in the southern and central-western regions. These correspond to zones with dense urban development, traffic congestion, and significant reduction in green cover. In contrast, blue cold spots, located in

northern and eastern areas, reflect relatively better air quality and overlap with low-density or vegetated land.

The **Road Density R^2 Map** shows where AQI is best explained by road density, with high R^2 values (>0.54) indicating strong influence. These areas, mostly in central and northern Jaipur, are highly urbanized and show a strong link between vehicular infrastructure and poor air quality. Similarly, the **Sprawl R^2 Map** shows that on the city's fringe and in some central pockets, air pollution is significantly influenced by urban sprawl. These areas often exhibit low-density, uncoordinated development with high private vehicle dependency, further exacerbating emissions.

The **Sprawl Index Hotspot Map**, created using a composite field combining normalized road density and population density values, reveals that urban edges—particularly in the south and northwest—are emerging as significant sprawl hotspots. These spatial clusters overlap with AQI hotspots, reinforcing the conclusion that urban sprawl plays a critical role in worsening air quality.

To determine whether AQI is more strongly influenced by road density or population density, a **Max R^2 (P vs. R) Map** was generated. This comparison helps in isolating dominant contributing factors across space. Finally, the **Max R^2 Hotspot Map** applies Gi* statistics to the highest R^2 values from either predictor, identifying statistically significant zones that demand immediate attention for urban planning and environmental regulation.

Methodology Reference:

- **Spatial Data Preparation**: Land use/land cover maps, road density grids, and population density layers were standardized to a common resolution (1 km^2 fishnet).
- **GWR Analysis**: Conducted in ArcGIS Pro, using AQI as the dependent variable and road density, population density, and sprawl index as independent variables.
- **Hotspot Analysis**: Applied the **Getis-Ord Gi*** statistic with a **fixed distance band of 1000 meters** to detect statistically significant clusters for AQI, sprawl index, and R^2 values.
- **Composite Index**: The sprawl index was constructed by normalizing and summing road density and inverse population density to capture low-density, high-dispersal development patterns.

4.9.2 MAJOR IMPACTED AREA

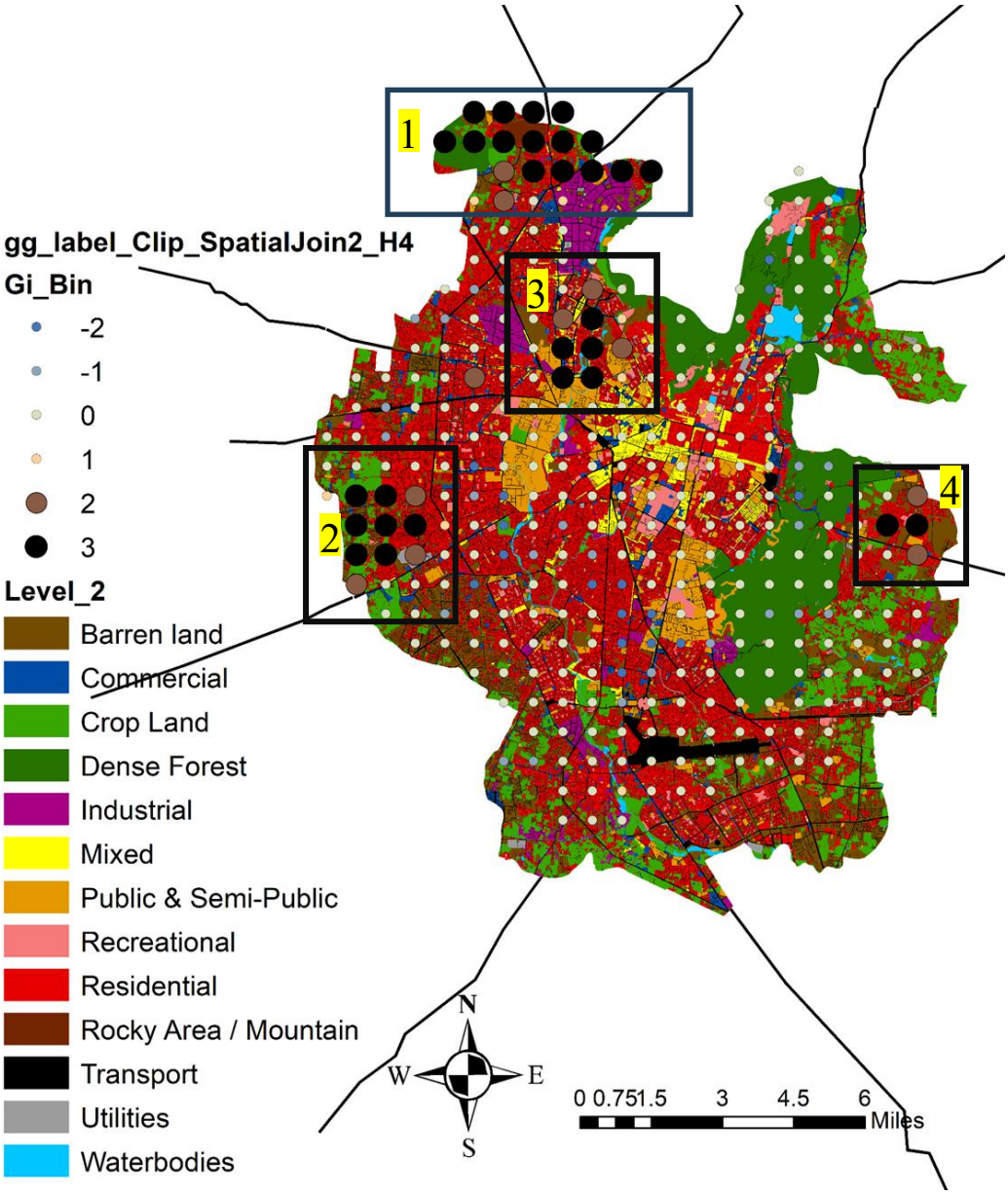


Figure 24 Land-Use map 2024

The above land use map of Jaipur city integrates land classification with spatial hotspot analysis to examine the influence of urban growth on ambient air quality. This composite map illustrates the intricate relationship between urban land transformation and pollution hotspots, offering critical insight into the city's environmental challenges driven by sprawl.

A diverse set of land use categories is visible, ranging from **residential, commercial, educational, and transport** to **agricultural, forest, waterbodies, and vacant lands**. Each

land use reflects specific anthropogenic or ecological processes at play. However, the **superimposed black dots** represent spatial **hotspot clusters**—identified using **Getis-Ord Gi*** statistical analysis—where **urban growth is significantly correlated with deteriorating air quality** at high confidence levels (95% to 99%). These hotspots capture spatial concentrations where urban expansion has notably contributed to elevated AQI (Air Quality Index) values.

KEY OBSERVATIONS

1. **Concentration of Hotspots in Urbanizing Frontiers:**
   The majority of the hotspot locations are observed in **northern, western, and southeastern peripheral zones** of Jaipur. These areas are undergoing **intensive urban development**, replacing erstwhile green zones such as cropland, open space, and scrublands. The loss of vegetation cover reduces the city's natural pollution sink capacity and exacerbates urban heat island effects.
2. **Transformation of Land Use in Hotspot Zones:**
   The hotspot areas align with a transition in land use from **vacant or agricultural lands** (e.g., cropland, dairy, horticulture) to **built-up urban fabric** (e.g., residential, commercial, utilities, and transport infrastructure). This transition implies increased impervious surfaces, higher energy use, and more vehicular dependence—all contributing factors to rising pollution levels.
3. **Expansion of Road Network and Vehicular Emissions:**
   The city's expanding **transportation infrastructure**—both road networks and transportation nodes—is evident in the land use distribution. Peripheral growth leads to **longer commute distances**, fostering increased **private vehicle usage**, particularly in areas where public transportation is lacking. Emissions from these vehicles contribute significantly to PM10 and NO_2 levels, directly impacting AQI values in newly urbanizing sectors.
4. **Residential and Mixed Land Use Intensification:**
   The largest land use category, **residential areas**, shows a strong correlation with pollution hotspots. In Jaipur's case, new residential townships in the outer zones tend to be **low-density and car-dependent**, which correlates with **higher AQI readings** due to increase per capita emissions. Additionally, **mixed land use zones**, where residential, commercial, and transport activities coexist, show elevated activity levels and concentrated pollution sources.

5. **Loss of Green Buffer Zones:**

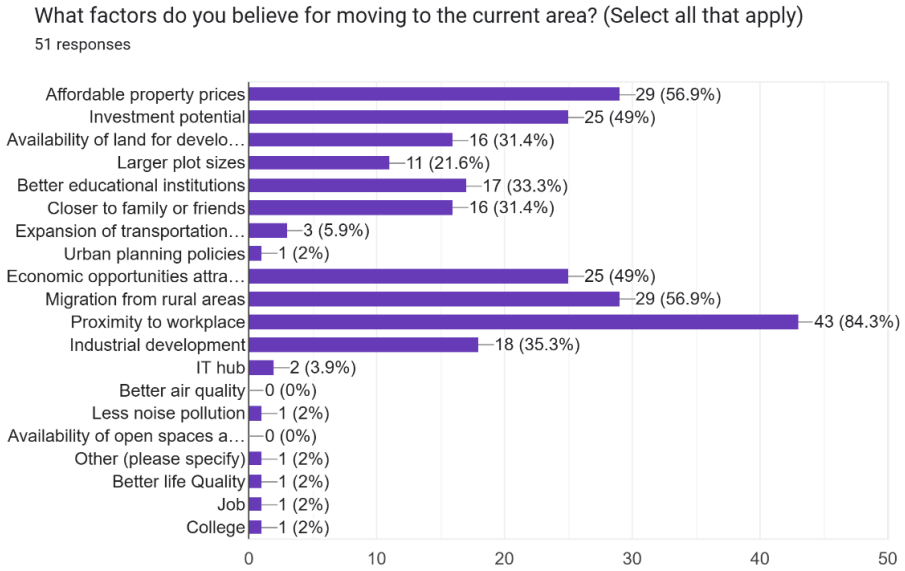
   Natural buffers such as **dense forests, croplands, waterbodies**, and **public open spaces** are shrinking in areas experiencing sprawl. This loss not only limits pollutant filtration but also reduces ecological resilience. In contrast, zones with preserved green spaces in the city's eastern and southern sectors correspond with **cold spots** (areas of statistically lower AQI), affirming the positive role of green cover in urban air quality regulation.

Implications for Urban Planning and Environmental Management:

This spatial overlay of **land use and AQI hotspot analysis** reveals how urban land development patterns are intrinsically linked to the city's air quality dynamics. The emerging urban edges, which are growing without proportionate infrastructure and regulatory checks, are becoming **pollution-prone zones**. These findings emphasize the necessity of integrating **environmental considerations into master planning.**

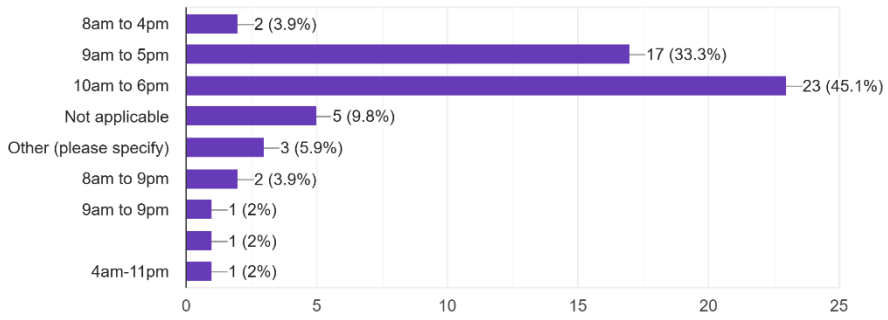
4.10 ANALYSIS OF FIELD SURVEY

For the responses the survey questions were divided based on Urban growth, Use of vehicles, consumption of fuel, spend time in traffic



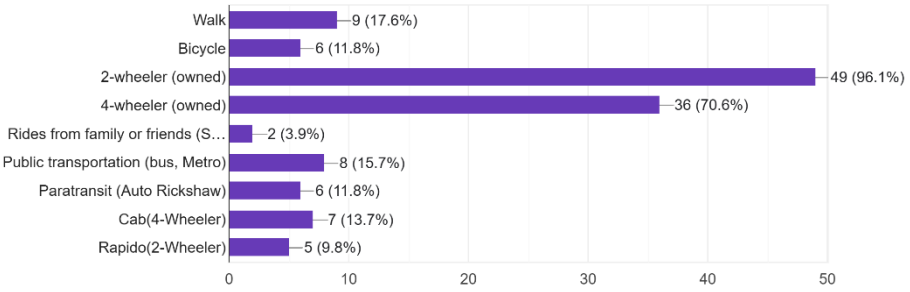
If you are doing office job, what is the time period of your job?

51 responses



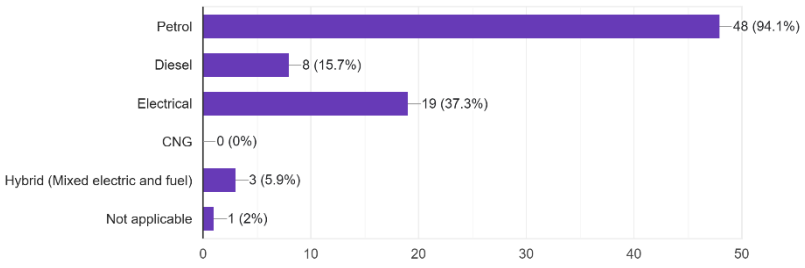
What type of Transportation mode do you use? (Select all that apply)

51 responses



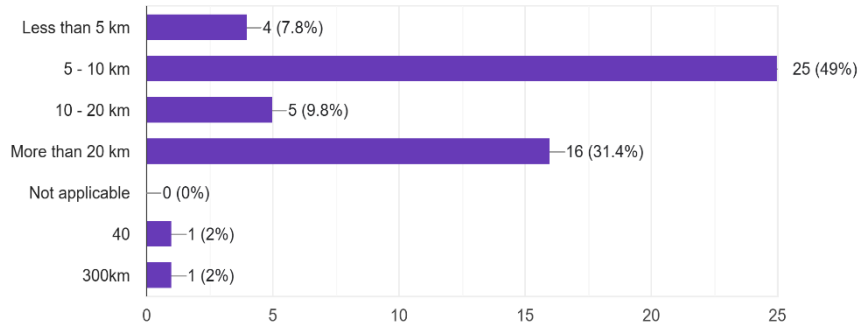
What is the Fuel type of your vehicle? (Select all that apply)

51 responses



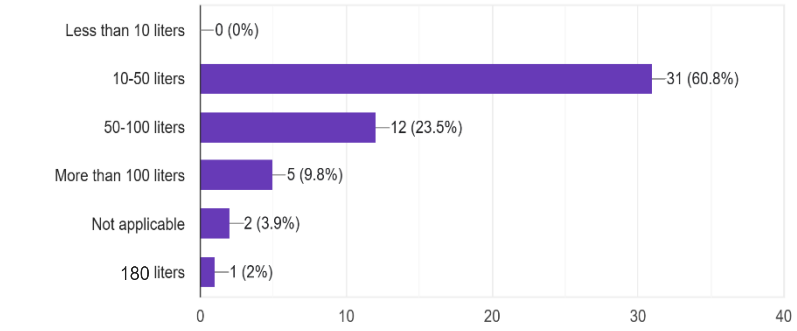
If you use a 2-wheeler, what distance do you prefer to travel? (Select all that apply)

51 responses



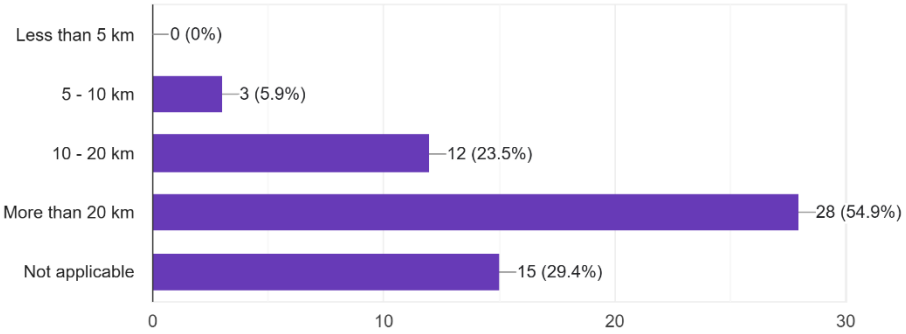
Average fuel consumption per month (liters or kWh for EVs)

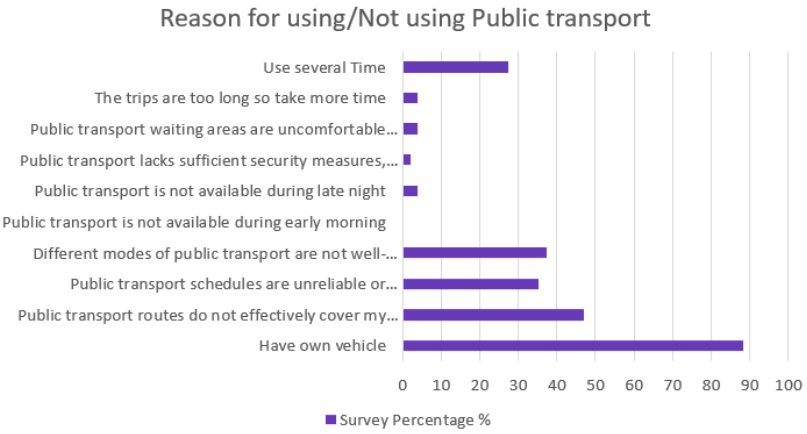
51 responses



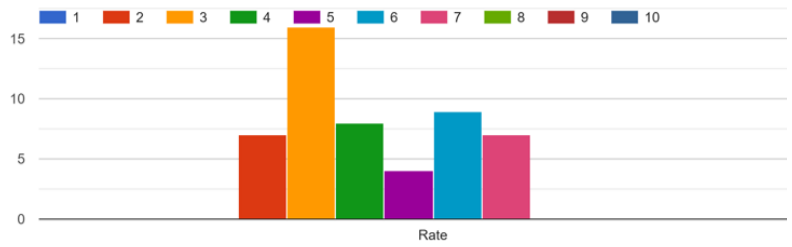
If you use a 4-wheeler, what distance do you prefer to travel? (Select all that apply)

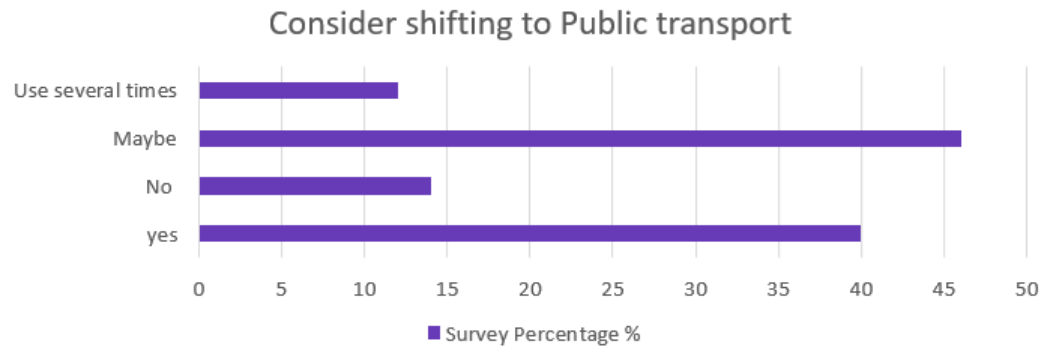
51 responses




Reason for using/Not using Public transport
Use several Time
The trips are too long so take more time
Public transport waiting areas are uncomfortable...
Public transport lacks sufficient security measures,...
Public transport is not available during late night
Public transport is not available during early morning
Different modes of public transport are not well-...
Public transport schedules are unreliable or...
Public transport routes do not effectively cover my...
Have own vehicle
0 10 20 30 40 50 60 70 80 90 100
Survey Percentage %

On a scale from 1–10, how dissatisfied or satisfied are you with the availability of the public transport service? Rate (1 is for dissatisfied & 10 for highly satisfied)





Jaipur's rapid population growth-driven by affordable property, industrial development, and rural migration-has intensified reliance on private vehicles, particularly two-wheelers (used for 5–10 km trips) and four-wheelers (for longer commutes). This surge in vehicular traffic, especially during peak hours (9–10 AM and 5–6 PM), has exacerbated congestion in commercial hubs like Rambagh Circle, Badi Chaupar, and Johari Bazar, where narrow roads struggle to accommodate high traffic volumes. Fuel consumption patterns reflect this dependency: most users consume 10–50 liters/month, while salespersons and long-distance drivers use up to 100 liters. Limited public transport coverage in peripheral areas and irregular bus schedules further push residents toward private vehicles, despite higher emissions and congestion. However, in zones with reliable bus services, public transport remains preferred, underscoring the potential for expanded, efficient transit systems to reduce traffic pressure and pollution.

Key Findings

The spatial analysis of Jaipur City from 2000 to 2023 reveals a significant relationship between urban growth patterns and deteriorating air quality. The findings from various spatial datasets and analytical tools are summarized as follows

1. Spatio-temporal trends in air quality

- In the year 2000, satellite-derived AQI data showed relatively low air pollution levels across most parts of Jaipur city.
- The eastern region of the city, characterized by hilly terrain and dense forest cover, consistently maintained lower AQI values throughout the study period due to natural vegetation and limited urban development.
- By 2023, AQI levels had increased substantially, particularly in the western part of the city, marking a clear spatial shift in pollution hotspots.

2. Direction of Urban Growth and Built-up Expansion

- The urban sprawl growth map and built-up area change analysis indicated that Jaipur's spatial expansion predominantly occurred toward the western direction.
- The western periphery witnessed the highest transformation from non-built-up to built-up areas between 2000 and 2023.
- This directional growth reflects a horizontal expansion pattern, typical of urban sprawl, characterized by low-density development.

3. Population Density and Urban Sprawl

- The population density map revealed that newly developed western areas exhibit low population density, confirming the presence of urban sprawl.
- These sprawled areas extend outward from the city core, with dispersed residential developments and lack of compact urban form.

4. Road Network and Transport Dependence

- The road density map showed a concentration of roads expanding in the western direction, aligned with the built-up expansion pattern.
- A major national highway connecting Delhi to Ahmedabad via Jaipur passes through the western part of the city, significantly increasing vehicular movement in the area.
- Peripheral areas, especially in the west, lack adequate public transport infrastructure, resulting in heavy reliance on private vehicles, contributing to increased vehicular emissions.

5. Road Infrastructure and Dust Emissions

- The poor quality of road infrastructure in the peripheral western areas was observed, leading to frequent generation of road dust, a major contributor to particulate matter (PM) pollution.
- The spread of construction activities in these newly developed areas further aggravates dust pollution due to building material transportation and on-site emissions.

6. Industrial Contribution to Air Pollution

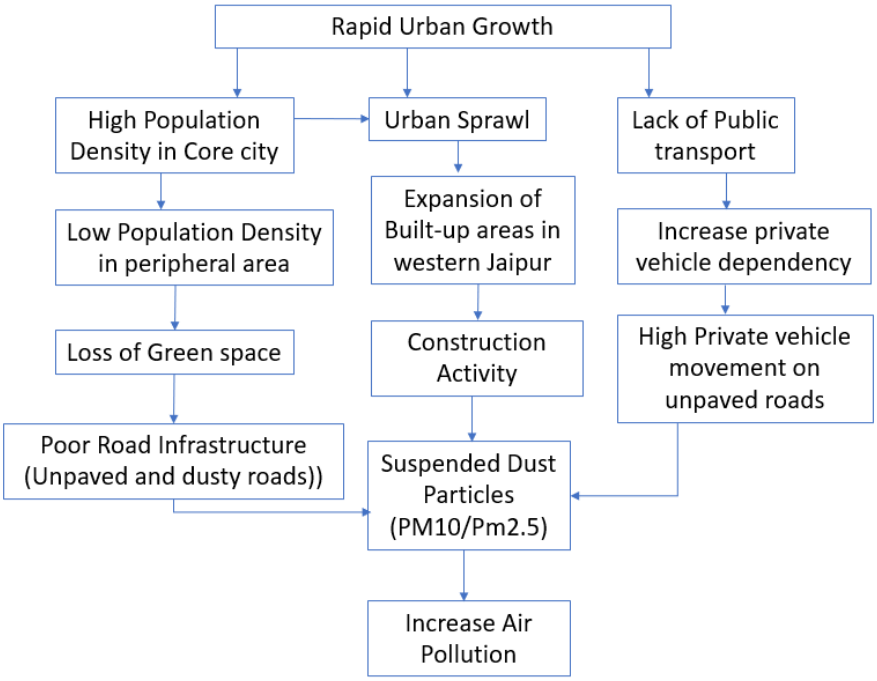
- The northwestern part of Jaipur hosts several industrial areas which have contributed to localized spikes in AQI levels.
- Emissions from industrial processes, coupled with the prevailing wind direction, likely influence the deterioration of air quality in adjacent residential zones**.**

5 RECOMMENDATIONS AND PROPOSALS:

Urban Planning Proposals to Mitigate Air Pollution from Urban Sprawl in Jaipur

Based on the spatial analysis of AQI, road density, and urban sprawl patterns, the following proposals are recommended to reduce air pollution in Jaipur's peripheral areas and promote sustainable urban growth:

THE URBANIZATION–POLLUTION NEXUS: JAIPUR'S CASE


Rapid Urban Growth
High Population Density in Core city
Urban Sprawl
Lack of Public transport
Low Population Density in peripheral area
Expansion of Built-up areas in western Jaipur
Increase private vehicle dependency
Loss of Green space
Construction Activity
High Private vehicle movement on unpaved roads
Poor Road Infrastructure (Unpaved and dusty roads))
Suspended Dust Particles (PM10/Pm2.5)
Increase Air Pollution

5.1 POLICIES TO CONTROL AIR POLLUTION IN JAIPUR

1. **Jaipur Air Quality Management Action Plan (2021)** — No zoning-based implementation strategy; sweeping and greening only in high-visibility areas (Board R. S., 2021).
2. **NCAP (2019)** – Recommends city-specific pollution mitigation plans, but Jaipur's lacks spatial targeting (Ministry of Environment, 2019).
3. **IITM's AQEWS** – Exists for Jaipur but not integrated into local policy planning ((IITM), 2023).
4. **CSE's Urban Mobility Report (2023)** – Jaipur's sprawl areas show **highest private vehicle use** due to **poor transit coverage** ((CSE), 2023).

5. **CPCB (2022)** – Road dust remains the **largest contributor to PM10 in Jaipur**, especially in areas with construction and unpaved roads (Board C. P., 2022).

Policy/Report & Year	Key Areas in Jaipur	Allocated Funds (INR)	Working Status	Gaps
Jaipur Air Quality Management Action Plan (2021)	High-visibility areas (Ajmeri Gate, Chandpole, Mansarovar), industrial clusters (Sitapura, VKIA)	Part of NCAP funds	Partially	No zoning-based strategy; neglects peripheral/construction zones. PM_{10} still exceeds standards.
NCAP (National Clean Air Programme), 2019	Citywide (non-attainment city), with focus on industrial, vehicular, and construction sectors	₹11.211 Cr (by 2024)	Partially	Lacks spatial targeting; PM_{10} reduction limited (18–22% since 2019).
IITM's AQEWS (Air Quality Early Warning System), 2023	Citywide forecasts and source apportionment; hotspots: Vishwakarma Industrial Area, Ajmer Road, Triven Road	Funded by MoEFCC	Underutilized	Not integrated into local policy; forecasts not used for proactive measures.
CSE's Urban Mobility Report (2023)	Urban sprawl areas (Jagatpura, Mansarovar, Sitapura periphery)	N/A (CSE report)	No	Poor transit coverage in sprawl zones; no mitigation for high private vehicle use.
CPCB Road Dust Findings (2022)	Construction zones (Sitapura, VKIA), unpaved roads (Agra Road, Jaipur-Kishangarh Highway), high-silt roads	Municipal funds	No	Dust control measures irregular; limited to central areas; unpaved roads persist.

Table 11 Policy/Report for controlling Air pollution in Jaipur

5.1.1 This proposal is not covered under existing policies

Policy Area	Jaipur Policy Exists?	Gap Identified	Why This Proposal Is Needed
Mechanized road sweeping	Yes (limited)	Only in city core	Sprawl areas with bad roads remain untreated
Green buffers & road repair	Partially	No GIS-based targeting	Not applied based on AQI or land-use data
Construction dust regulation (C&D Rules)	Yes	Enforcement weak	No integration with AQI hotspot maps
Public transport to peripheral areas	Planned (not delivered)	Poor last-mile and expansion	Peripheral sprawl is vehicle-dependent
AQI monitoring (AQEWS)	Exists	Not linked to action zones	No spatial action plan made from AQEWS data

Table 12 Proposals that not covered under existing policies

5.2 PROPOSAL 1

"ROAD INFRASTRUCTURE IMPROVEMENT AND DUST CONTROL MEASURES"

5.2.1 WHAT THIS PROPOSAL ADDRESSES

FRAMEWORK

- **GIS-based analysis (GWR, sprawl index, road density, AQI maps)** to identify **priority intervention zones**.
- Propose **localized dust mitigation** (repair, greening, sweeping, suppression).
- Target **public transport interventions** to **urban fringe zones** with highest emissions and dependency on private transport.

5.3 STRENGTHENS OF PROPOSAL

Thesis Element	Alignment with Proposal
Impact of Urban Growth	Identifies real effects of sprawl on road dust and AQI
Policy Evaluation	Highlights existing gaps and implementation failures
Spatial Analysis	Uses GWR, sprawl index, AQI overlays for intervention
Recommendation Section	Offers an actionable, policy-relevant solution not currently implemented

Table 13 Strengthens of proposal

5.3.1 HOTSPOT LOCATIONS

LOCATION1

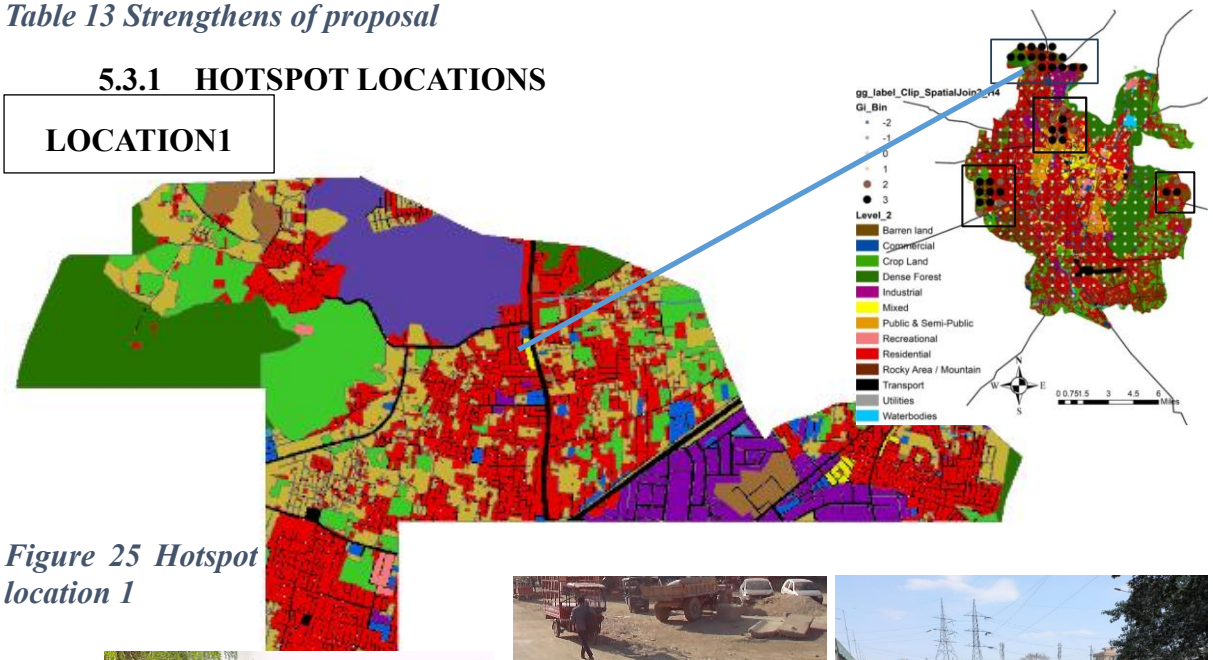
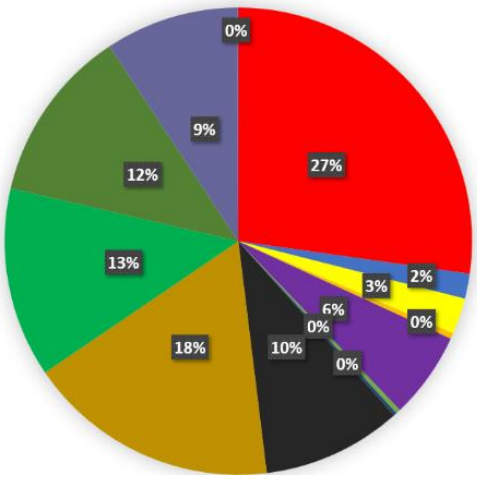


Figure 25 Hotspot location 1

LAND USE AREA

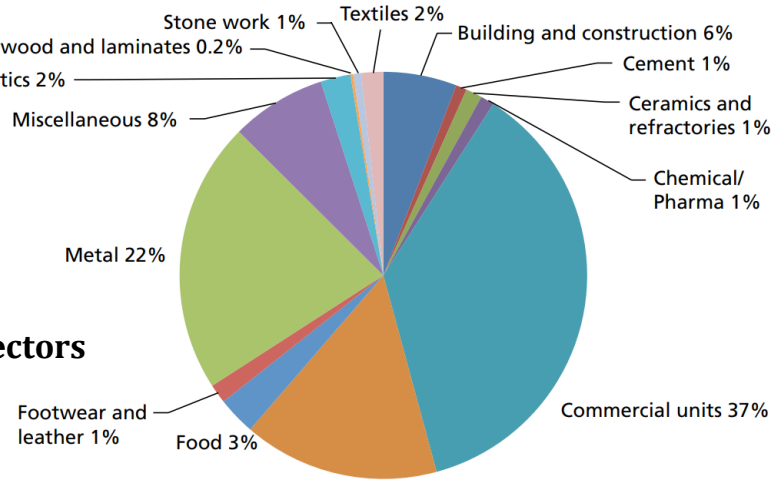


- Residential
- Commercial
- Public & semi public
- Recreational
- industrial area
- Mixed use
- Utilities
- Transportation
- Barren Land
- Crop Land
- Dense forest
- Rocky area
- Water bodies

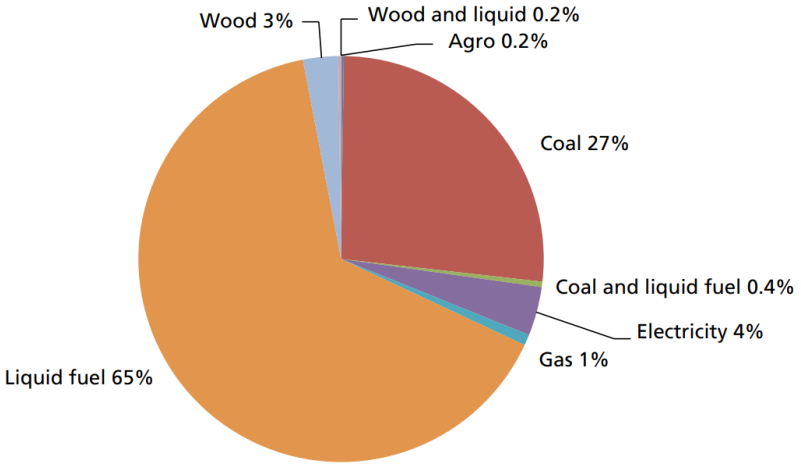
VISHWAKARMA INDUSTRIAL AREA – One of the major contributors of Air pollution in this area.

- **V.K.I.A (Vishwakarma Industrial Area)** established by **RIICO in 1970**.
- Covers around **14.69 km²**.
- Well-developed infrastructure:
  - Connected to **NH 11** and a **State Highway**
  - Some **internal roads are poorly maintained**
- **463 air-polluting industries** operate in the area.

Industrial sectors



Fuel usage



5.3.2 JUSTIFICATION FOR AQI HOTSPOT AREA 1

The spatial analysis of land use within AQI hotspot zones in Jaipur reveals critical insights that directly support the recommendation to improve road infrastructure and implement dust control strategies.

A significant portion of the hotspot area is designated for **transportation use**, covering approximately **1.2 million m²**, indicating the presence of a dense road network. Additionally,

the cumulative **shape length of road segments exceeds 315 kilometres**, suggesting extensive surface exposure to vehicle movement and potential dust re-suspension. These conditions are consistent with elevated concentrations of particulate matter ($PM_{2.5}$ and PM_{10}), which are key contributors to poor air quality in the city.

Moreover, **residential areas** account for the largest share of land use within the hotspot zone (**3.4sqr km**), followed closely by **barren lands** (**2.2sqr km²**). These areas are especially vulnerable to air pollution due to their proximity to emission sources and the presence of exposed, unpaved surfaces that act as dust reservoirs. Without vegetation or dust suppression mechanisms, these lands contribute significantly to suspended particulate matter, especially during the dry season and under high vehicular movement.

The presence of **industrial (14.69 km²)** and **commercial (.216 km²)** zones within the AQI hotspots further exacerbates emissions, as these areas typically witness high traffic volumes, including heavy-duty vehicles that degrade road surfaces and stir up dust. Conversely, **natural dust buffers** such as forests and water bodies are severely limited in these areas, with **dense forests** covering only **1.5 km²** and **water bodies** a negligible **7,000 m²**. This lack of ecological balance amplifies the retention and spread of air pollutants.

LOCATION 2

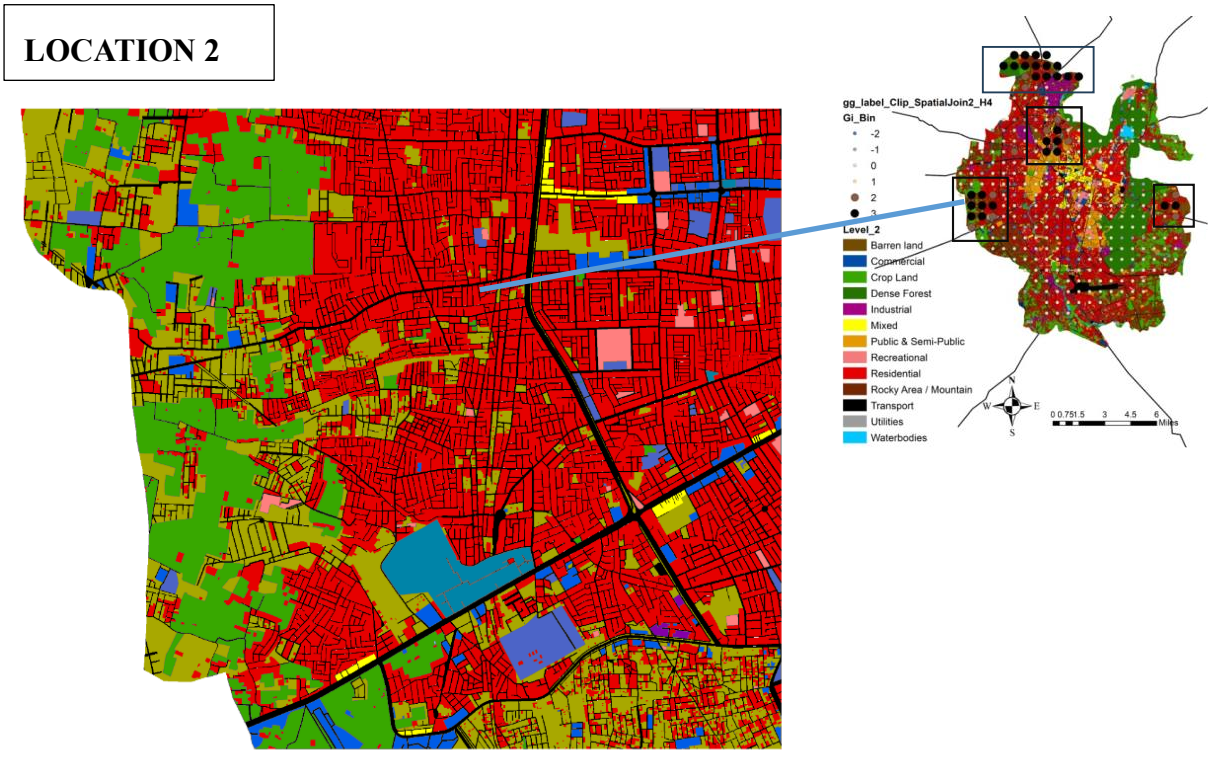
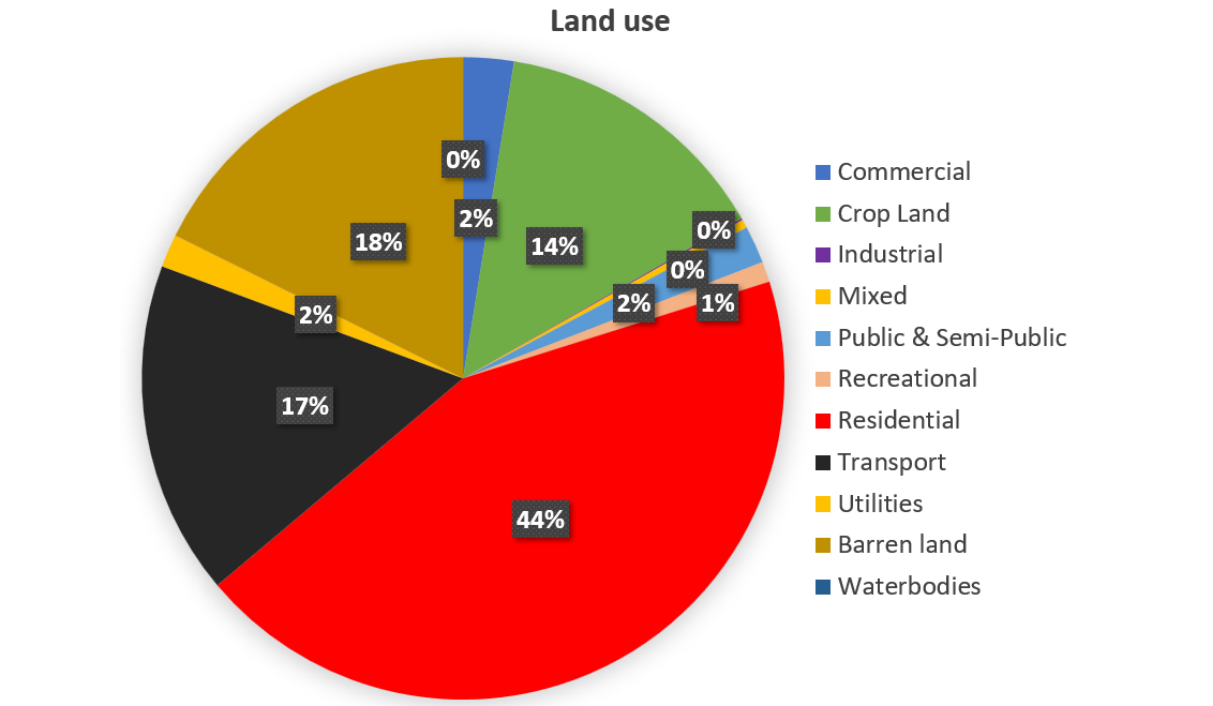


Figure 26 Hotspot location 2



5.3.3 JUSTIFICATION FOR AQI HOTSPOT AREA 2

The Land Use Land Cover (LULC) data provides crucial insights into the pattern of land utilization in Jaipur city, which directly influences urban air quality. The highest **shape area** is covered by **residential land use**, accounting for approximately **1,127,744 sq.m**, which confirms that a significant portion of Jaipur's land is occupied for housing. This supports the fact that population growth (at a rate of **2.73% annually**) is driving residential expansion, especially toward the peripheral western part of the city. As this area develops, it creates low-density sprawl, contributing to longer travel distances and greater reliance on motorized transport.

Following residential areas, **transport infrastructure** occupies the second-largest land area (**433,751 sq.m**) and has the **highest shape length (939,455 m)**. This indicates an extensive road network spread throughout the city. Despite the high road coverage, the peripheral areas still suffer from **poor road quality**, many of which are **unpaved** or **underdeveloped**, leading to high **road dust** emissions — a major source of **PM10 particles**, especially in dry seasons. This aligns with field observations and research stating that **paved roads reduce airborne dust significantly compared to unpaved ones**.

Barren land, covering **455,267 sq.m**, further worsens the dust problem. These open lands are often found near construction sites or undeveloped fringes, particularly in western Jaipur. Due to minimal vegetation, such areas are prone to **dust storms** and **wind-blown particles**, which increase the particulate matter in the surrounding atmosphere.

On the other hand, **green and recreational areas** (only **264,671 sq.m**) and **water bodies** (**296 sq.m**) are extremely limited. This lack of ecological buffer zones reduces the city's ability to **absorb air pollutants** or regulate microclimates, worsening the overall air quality. The **scarcity of green spaces** also reflects poor integration of sustainable urban planning principles in the city's expansion model.

Industrial areas, although smaller in area (**23,433 sq.m**), are concentrated primarily in the **northwestern region**, and contribute significantly to localized air pollution due to industrial emissions. These zones are often poorly buffered by green spaces or emission control infrastructure, leading to higher AQI levels in their surroundings.

Utilities and **public & semi-public facilities**, with areas of **42,872 sq.m** and **487,280 sq.m** respectively, play supporting roles in urban function but are not major direct contributors to pollution unless improperly managed.

Finally, **crop land** (**364,978 sq.m**) and **mixed-use areas** (**109,172 sq.m**) are still present in patches, likely on the urban-rural fringes. These are under increasing pressure from urban expansion and may eventually be converted into residential or commercial uses, further stressing infrastructure and increasing emissions from construction and transport activities.

Table 14 summarizes relevant studies that support the proposed interventions in road infrastructure and dust control, particularly in the context of urban AQI hotspot management.

S.No.	Study / Source	Focus Area	Key Findings	Relevance to Recommendation
1	Guttikunda & Jawahar (2012) – Atmospheric Environment	Indian cities (incl. Jaipur)	Resuspended road dust contributes up to 40% of PM_{10} in urban areas.	Emphasizes need for improved road surfacing and regular maintenance to reduce particulate emissions.
2	U.S. EPA (2006) – AP-42 Emission Factors	Paved/unpaved roads	Water spraying and mechanical sweeping can reduce road dust emissions by 40–60%.	Validates dust control techniques as effective mitigation strategies in hotspot zones.
3	Abhijith et al. (2017) – Atmospheric Environment	Global urban areas	Vegetation along roadsides reduces airborne particulates and wind re-entrainment.	Supports green infrastructure as part of road improvement projects.
4	Jain et al. (2020) – Environmental Monitoring and Assessment	Urban India	Barren land and dry open spaces increase $PM_{2.5}$ and PM_{10} levels.	Highlights importance of dust stabilization in undeveloped and roadside areas.
5	World Bank (2014) – Urban Air Quality in South Asia	South Asia	Road condition improvements are low-cost, high-impact interventions for pollution control.	Encourages investment in road infrastructure as a primary urban air quality management tool.

Table 14 Case studies that used road infrastructure improvement to control Air pollution

The following table outlines a comprehensive implementation plan for the proposed road infrastructure improvement strategy, addressing environmental, social, economic, governance, and financing dimensions:

5.3.4 IMPLEMENTATION FRAMEWORK FOR AQI HOTSPOT AREAS

Component	Details
Proposal Title	Road Infrastructure Improvement and Dust Control Measures
Goal	Reduce $PM_{2.5}$ and PM_{10} levels by improving road conditions and limiting dust re-suspension in hotspot zones

Table 15 Implementation framework

5.3.5 STRATEGIC DIMENSIONS

Dimension	Key Strategies
Environmental	• Pave unsealed roads to minimize dust emissions • Use climate-resilient, low-dust materials • Incorporate roadside vegetation (bio-barriers) for dust suppression
Social	• Reduce respiratory health impacts in residential areas • Improve walkability and safety, especially for vulnerable populations • Engage communities in maintenance awareness
Economic	• Long-term cost savings through durable infrastructure • Reduce healthcare costs due to pollution-related illness • Support local labor and materials market through job creation

Table 16 Strategic Dimension

5.3.6 IMPLEMENTATION FRAMEWORK

Aspect	Mechanism
Governance	• Jaipur Municipal Corporation (JMC) to lead planning and execution • Coordination with Rajasthan Pollution Control Board (RPCB), Public Works Department (PWD), and Urban Local Bodies (ULBs) • Integration with Smart City and AMRUT mission plans
Monitoring & Evaluation	• Baseline and post-implementation AQI monitoring at key junctions • Geo-tagging of upgraded road segments • Quarterly progress reporting with public dashboards • Independent audit of construction quality and maintenance adherence

Table 17 Implementation framework

5.3.7 FINANCING MECHANISMS

Source	Details
Public Funds	• State government urban infrastructure budget • Smart Cities Mission & AMRUT (Atal Mission for Rejuvenation and Urban Transformation) funding • PMAY-U (Pradhan Mantri Awas Yojana – Urban) for related infrastructure in residential areas
Private Sector / PPP	• Public-Private Partnerships for construction and maintenance • Local contractor engagement under build-operate-maintain (BOM) models
Multilateral/Donor Funds	• Funding from institutions like the World Bank, ADB for climate-resilient infrastructure • Grants for urban air quality from environmental trusts (e.g., Clean Air Fund)

Table 18 Financing Mechanisms

5.3.8 INCENTIVES & REVENUE OPTIONS

Type	Details
User Incentives	• Tax rebates for private developers who include dust mitigation (e.g., paved access roads) in large residential projects • Awards for "clean road zones" via resident welfare associations (RWAs)
Tax/Levy Options	• Introduction of **Urban Road Maintenance Cess** on vehicle registration or property tax • Environmental Impact Fee on polluting commercial fleets, dedicated for road upgrades • Advertisement rights on green medians to generate maintenance funds

Table 19 Incentives & Revenue Options

5.3.9 POLICY AND PLANNING IMPLICATIONS

Urban air quality management is a multidimensional challenge that requires strong coordination between environmental regulation, urban infrastructure development, and spatial planning. The findings of this study — particularly the spatial relationship between urban sprawl, road infrastructure quality, and AQI hotspots — carry significant implications for city-level policy and governance in Jaipur.

I. INTEGRATION WITH JAIPUR MASTER PLAN

The Jaipur Master Plan emphasizes infrastructural expansion and land use planning but pays limited attention to air quality metrics. The spatial analysis in this thesis highlights the need to integrate air pollution indicators like AQI, road dust emissions, and population density into land use zoning and transport corridor planning. This integration can help in regulating urban sprawl and prioritizing infrastructure upgrades in pollution-prone zones.

II. SUPPORT FOR NATIONAL CLEAN AIR PROGRAMME (NCAP) GOALS

The proposed strategies directly align with the objectives of the NCAP, which aims to reduce PM concentrations in non-attainment cities (like Jaipur) by 20–30% over five years. By identifying AQI hotspots and linking them to land use and infrastructure deficits, this study offers a data-driven framework for localizing NCAP targets and interventions.

III. LEVERAGING SMART CITIES AND AMRUT MISSIONS

The recommendations such as road surface improvement, dust control measures, and spatial monitoring align well with the Smart Cities Mission's emphasis on liveability, and AMRUT's focus on infrastructure and environmental sustainability. Spatial AQI monitoring and road upgrading can be mainstreamed into the investment priorities of these schemes.

IV. NEED FOR MULTI-AGENCY COORDINATION

Managing urban air quality demands coordination between:

- Jaipur Municipal Corporation (JMC) – for urban roads and solid waste management

- Rajasthan Pollution Control Board (RPCB) – for AQI monitoring and enforcement
- Urban Local Bodies (ULBs) – for local land use regulation and construction practices
- Transport departments and Traffic Police – for enforcement of speed control, dust suppression, and emissions control

A joint action task force can ensure synchronized planning, budgeting, and implementation of air quality interventions.

V. INSTITUTIONALIZING GIS-BASED MONITORING AND DECISION-MAKING

This study demonstrates the effectiveness of GIS-based analysis in identifying pollutant hotspots and infrastructure gaps. Institutionalizing spatial tools like GWR, sprawl index mapping, and hotspot overlays within municipal planning departments can greatly enhance evidence-based policymaking and resource prioritization.

5.4 PROPOSAL 2

"ESTABLISH VEGETATIVE BUFFER ZONES AND GREEN CORRIDORS"

5.4.1 JUSTIFICATION

Vegetative buffers—such as tree-lined streets, green belts, and roadside plantations—act as natural barriers that help trap airborne particulate matter and reduce the spread of road dust and vehicular emissions. In the hotspot areas identified in this study, particularly those with dominant transport and residential land uses, the lack of green cover contributes significantly to elevated AQI levels.

The urban fringe zones of Jaipur, which exhibit characteristics of sprawl and increased road length per capita, often lack ecological integration in their spatial structure. Establishing green buffers in these areas offers multiple benefits: improving air quality, reducing the urban heat island effect, enhancing pedestrian environments, and supporting local biodiversity.

Research has shown that vegetation can reduce PM concentrations by up to 25% in transport corridors, especially when properly selected and strategically planted (Abhijith et al., 2017). Integrating such green infrastructure into Jaipur's land use framework aligns with sustainable urban development principles and supports national environmental missions.

5.4.2 KEY STRATEGIES

- Plant native and dust-tolerant tree species (e.g., Neem, Ficus, Peepal) along major roads and in high-AQI zones.
- Develop green medians and roadside plantations in peripheral urban areas and transport corridors.
- Integrate green infrastructure mandates into zoning regulations and development control rules.
- Encourage public-private partnerships (PPPs) for the creation and maintenance of vegetative corridors.
- Utilize GIS-based spatial analysis to identify and prioritize locations for buffer implementation.

5.4.3 IMPLEMENTATION FRAMEWORK

Aspect	Details
Environmental	Reduction in PM10 and PM2.5 levels Localized cooling Carbon sequestration.
Social	Healthier neighborhoods Improved aesthetics Shade for pedestrians.
Economic	Low maintenance cost Increased property values Reduced health expenditure.
Governance	Led by Jaipur Municipal Corporation (JMC) To be incorporated into the Master Plan and building regulations.
Monitoring	Use of GIS-based vegetation mapping and AQI sensors Annual performance audits.
Financing	Funding from AMRUT and Smart Cities Mission CSR initiatives from private developers and institutions.
Incentives/Tax	Incentives for private landowners maintaining green spaces Introduction of a green maintenance fee or rebate system.

Table 20 Implementation framework for proposal 2

5.5 PROPOSAL 3

“PROMOTE PUBLIC TRANSPORT ACCESSIBILITY AND MODAL SHIFT”

5.5.1 JUSTIFICATION

Urban sprawl in Jaipur has resulted in longer travel distances and increased dependency on private vehicles, particularly in peripheral zones. This has significantly contributed to elevated AQI levels due to higher emissions of PM2.5 and PM10 from motorized transport. Promoting a modal shift from private vehicles to cleaner and more efficient public transport systems is essential to reduce vehicular pollution, improve mobility, and enhance environmental sustainability.

This recommendation aligns with the National Urban Transport Policy (NUTP) and the objectives of the Smart Cities Mission, which emphasize reducing pollution through improved public transit access. It also complements the findings of this study, where AQI hotspots were linked to poor public infrastructure and low public transport integration in low-density sprawled areas.

5.5.2 KEY STRATEGIES

- Expand and improve public bus and metro feeder routes to peripheral and underserved areas.
- Develop park-and-ride systems near outer zones to encourage a modal shift from personal to public transport.
- Enhance last-mile connectivity through shared mobility (e.g., e-rickshaws, bicycle lanes).
- Prioritize electric and CNG-based buses to reduce direct emissions from public transport fleets.
- Integrate AQI and traffic data in GIS to plan new routes in highly polluted or rapidly growing regions.

5.5.3 IMPLEMENTATION FRAMEWORK

Aspect	Details
Environmental	Reduction in vehicular emissions Decrease in AQI levels in transport corridors.
Social	Improved accessibility Time and cost savings for commuters Equity in mobility.
Economic	Long-term reduction in fuel costs Increased public transit revenue Reduced healthcare burden.
Governance	Led by Jaipur City Transport Services Ltd. (JCTSL) in coordination with JMC and urban planning authorities.
Monitoring	Use of GPS-based tracking and AQI monitoring to assess coverage and impact.
Financing	Central/state urban transport funding International development loans Private participation through PPPs.
Incentives/Tax	Subsidies on public transport passes Congestion tax in core areas to discourage car use.

Table 21 Implementation framework for Proposal 3

5.6 CONCLUSION OF

This thesis investigated the impact of urban growth on air quality in Jaipur city, focusing on how spatial factors such as population density, land use patterns, road infrastructure, and urban sprawl influence air pollution levels. By employing GIS-based spatial analysis, land use mapping, and AQI data, the study identified significant correlations between poor infrastructure in sprawled zones and elevated AQI levels—particularly due to dust emissions and vehicular dependency.

5.7 KEY FINDINGS

- Peripheral urban areas exhibited higher AQI values compared to central high-density zones due to poor road quality, greater reliance on private vehicles, and lack of green cover.
- Hotspot areas identified through Geographically Weighted Regression (GWR) showed strong spatial correlation between low population density, high road density, and degraded air quality.
- The Sprawl Index further revealed that fringe zones suffer from poor infrastructure, increased travel distances, and minimal ecological integration, all of which exacerbate pollution levels.

These findings highlight how unplanned urban expansion and neglected infrastructure directly contribute to deteriorating environmental conditions in growing Indian cities like Jaipur.

5.8 RECOMMENDATIONS SUMMARY

In response to the study's findings, three key recommendations were proposed to improve air quality and guide sustainable urban development:

- **Improve Road Infrastructure and Dust Control Measures**:

  Focused on paving unpaved roads, adopting climate-resilient materials, and reducing dust emissions through maintenance and speed control measures.

- **Establish Vegetative Buffer Zones and Green Corridors**:

  Recommended the strategic planting of native vegetation in transport corridors and urban fringes to reduce particulate matter and improve liveability.

- **Promote Public Transport Accessibility and Modal Shift**:

  Encouraged the expansion of public transit, development of last-mile connectivity, and use of cleaner transit technologies to reduce dependency on private vehicles.

Each proposal included detailed implementation strategies across environmental, social, economic, and governance dimensions, supported by tables outlining financing mechanisms, monitoring tools, and incentive structures.

5.9 LIMITATIONS OF THE STUDY

While the study provides a strong spatial foundation, limitations include:

- Use of static AQI data, without accounting for seasonal or temporal variation.
- Lack of source-specific emission data (e.g., industrial vs. vehicular).
- Behavioural data such as commuting habits and vehicle types were not integrated.

Future research could expand on these areas by incorporating temporal AQI trends, real-time emissions tracking, and surveys on transport behaviour.

CONCLUSION

This thesis contributes to the growing body of literature linking urban spatial form and environmental outcomes, offering a GIS-based methodology to assess the environmental consequences of urban growth. The findings and recommendations presented here provide actionable insights for urban planners, policymakers, and environmental authorities in Jaipur and similar cities undergoing rapid urbanization. Through targeted infrastructure improvement, ecological integration, and sustainable mobility planning, cities can mitigate the adverse effects of urban sprawl and pave the way toward healthier, more resilient urban futures.

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